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Dissolved organic carbon export from a cutover and restored peatland

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Abstract:

High demand for horticultural peat has increased peatland drainage and peat extraction in Canada. The hydrology and carbon cycling of these cutover peatlands is greatly altered, necessitating active restoration efforts to permit the regeneration of Sphagnum mosses and the re-establishment of natural peatland function. The effect of peatland extraction and restoration on the export of dissolved organic carbon (DOC) was examined for three successive seasons (May to October, 1999 to 2001) at two different sites (cutover and restored) in eastern Québec. A shift towards higher DOC concentrations was observed following peatland extraction (maximum: 182·6 mg L^{-1}) and concentrations remained high post-restoration (maximum: 191·0 mg L^{-1}). The cutover site exported more DOC than the restored site in all three study seasons. The highest exports occurred during the wettest year (1999), with cutover and restored site export of 10·3 and 4·8 g m^{-2}, respectively. In 2000, 8·5 g C m^{-2} was released from the cutover site, while the restored site released less than half that amount (3·4 g C m^{-2}). In 2001, the restored site released about the same amount of DOC as in the previous year (3·5 g C m^{-2}), while the cutover site load dropped to 6·2 g C m^{-2}. Both sites were net exporters of DOC in all years.

KEY WORDS dissolved organic carbon; peatland; restoration; drainage; dissolved organic matter; runoff

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INTRODUCTION

The demand for horticultural peat has recently increased peatland drainage and extraction activities in Canada (Cleary *et al*., 2005). Peatland drainage and extraction severely alter the hydrology (Price, 1997; Price *et al*., 1998; Schlotzhauer and Price, 1999) and by extension the CO_2 and CH_4 dynamics (Tuitilla *et al*., 1999; Waddington and Price, 2000; Waddington *et al*., 2002) of the peatland. Peatland drainage and vegetation removal alter the mechanisms that control evapotranspiration and runoff (Heathwaite, 1995; Van Seters and Price, 2001), while the peat that is exposed at the surface after extraction has a lower hydraulic conductivity, reducing groundwater flow within the peatland (Price and Whitehead, 2001). The increased aeration of the peat enhances oxidation thereby increasing bulk density and decreasing specific yield (Price, 1997). This drop in specific yield creates larger water table drawdowns and further enhances peat oxidation during dry periods (Waddington *et al*., 2002). These cutover peatlands have been especially impacted to the point where the natural regeneration of *Sphagnum* is no longer possible (Campeau and Rochefort, 1996) without active restoration (Rochefort *et al*., 2003). Active peatland restoration (see Rochefort, 2003 for details) involves blocking drainage ditches, creating peak dykes and adding a straw mulch protective cover to increase surface humidity thereby improving soil moisture and tension (Price *et al*., 1998) for *Sphagnum* growth, which is added as diaspores below the mulch during the restoration process. Consequently, peatland drainage, extraction, and restoration have large impacts on peatland water chemistry and export (Wind-Mulder *et al*., 1996). Of particular interest is the export of dissolved organic matter, including dissolved organic carbon (DOC).

DOC can have a profound impact on the acidity (Gorham *et al*., 1986; Urban *et al*., 1989), nutrient and pollutant transport (Thurman, 1985; Tipping, 1981; Kalbitz *et al*., 2000) of natural waters and can represent an important component of the carbon cycle of a peatland (Gorham, 1991). Several studies have examined DOC distribution patterns, export and quality from natural peatland ecosystems (Moore, 1987; Urban *et al*., 1989; Fraser *et al*., 2001) and noted that hydrology is the major control on DOC production, distribution and export in these ecosystems. For example, zones of high DOC concentrations in natural peatlands have been linked to areas receiving upland nutrients (Moore, 1987) and areas of high evapotranspiration (Moore, 1987; Waddington and Roulet, 1997). Consequently, the changes in hydrology and peat decomposition following peat extraction and restoration are likely to have large impacts on DOC export and dynamics. However, while Glatzel *et al*. (2002) examined the relationship between CO_2 emissions and DOC concentrations in abandoned cutover and restored

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peatlands, no study has been conducted on the effect of peat extraction and restoration on DOC export in peatlands. The objective of this paper is to determine the effect of peatland extraction and restoration on DOC export.

STUDY AREA

This study was carried out at the cutover and restored portions of the 210 ha Bois-des-Bel (BDB) peatland, located 14 km east of Rivière-du-Loup, Québec (47°58′N, 69°25′W) (Figure 1). An 11·5 ha portion of the bog was drained in 1972, separated into 11 approximately 30 m × 300 m peat fields, and cutover using the vacuum extraction technique from 1973 to 1980. The mean annual temperature is 3 °C and the mean January and July temperatures are −12 °C and 18 °C respectively (Environment Canada, 1993).

Restoration, as described by Rochefort *et al.* (2003), began in the autumn of 1999, separating the cutover (extracted) portion of the peatland into two catchments; a 7·2 ha restored section (peat fields 1 to 8) and a 1·8 ha cutover section (peat fields 9 to 11) (Figure 1). Peat dykes were constructed on the restored site to increase water retention during high flow periods. The dykes divided the restored area into four zones (Figure 1). Zones 2, 3 and 4 were restored in the autumn of 1999 and zone 1 was restored in 2000. Two shallow pools (maximum depth = 1·5 m, length = 13 m, width = 5 m) were also created in each of zones 1 to 4, to attract aquatic and amphibian species (Figure 1). Pond vegetation from a natural peatland pond was introduced into one of the pools in each zone in the summer of 2000. During restoration all vegetation from the restored site was cut and the surface of the peatland was milled. The cut vegetation, in many circumstances, was used as fill for the drainage ditches. Moss and vascular vegetation increased to 23% and

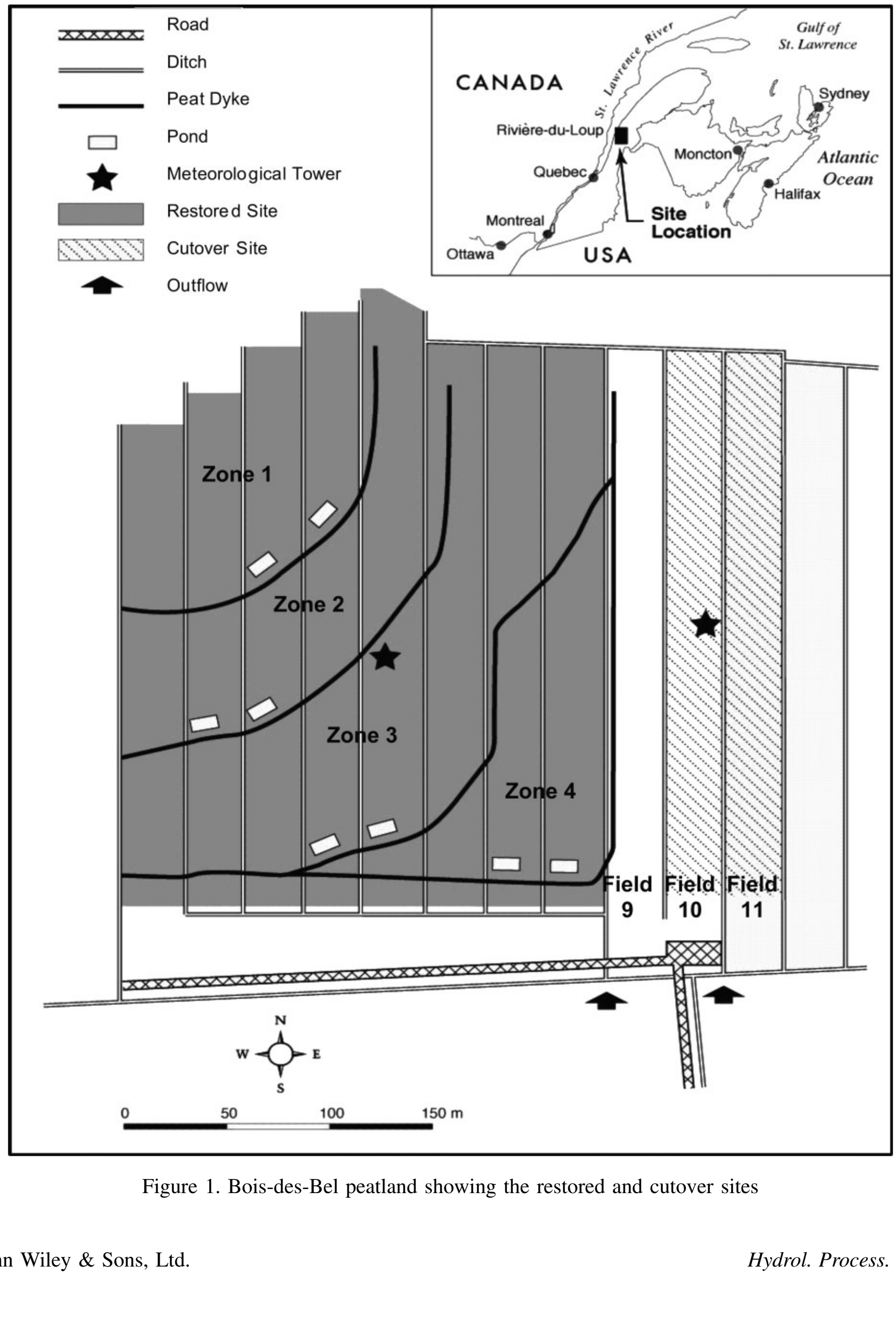

Figure 1. Bois-des-Bel peatland showing the restored and cutover sites

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10% of the restored site surface area respectively by 2001.

METHODOLOGY

DOC chemistry and hydrometric data were collected during the growing seasons (early May to mid- October) for three successive years (1999 to 2001). Snowmelt discharge and DOC chemistry were sampled from late March to the end of April, 2001. Three summer storms were also examined in 2001: a medium intensity storm with wet antecedent conditions in May (days 132 and 133), a high intensity storm with dry antecedent conditions in July (day 205) and a medium intensity storm with dry antecedent conditions in August (days 238 and 239).

Peatland hydrology

Stage was recorded continuously at the outflow ditches (Figure 1) in 1999 and 2000 using a potentiometric water level recorder, while in 2001 stage was recorded using a Remote Data System (RDS) water level recorder. Stage recorders were either placed in a V-notch bucket below the outflow or behind a V-notch weir. Discharge was measured by developing a stage-discharge rating curve at each outflow ditch and for each study season. Precipitation was measured using both a tipping bucket and a manual rain gauge at a meteorological station located in the restored site (Figure 1). During the 2001 snow melt period, the snow pack in the peatland melted before that of the adjacent agricultural ditch causing water to back-up in parts of the two main drainage ditches. During this time discharge from the cutover and restored sites was estimated using salt dilution experiments. These estimates corresponded well with direct discharge measurements when the culverts were only partially flooded.

Water sampling

Water samples from the catchment outflows were collected three times a week from May to October in each field season, while surface water samples from ditches and pools were collected once a week from early May to early October in 2001. Rainfall samples were collected after each rain event. Samples were filtered using 0·7 μm Whatman GF/F filters and stored at 4 °C until analysis. Subsamples for total DOC were stored in 7 mL glass vials and were transferred in coolers for analysis at the National Water Research Institute in Burlington, Canada. The remainder of the sample was stored in plastic cups at 4 °C until further analysis.

DOC analysis

DOC was analysed using high temperature catalytic oxidation using a Dohrmann DC-190 Total Carbon Analyser (Rosemount Analytical Inc., Dohrmann Div., Santa Clara, CA USA) or a Shimadzu TOC 5000A instrument (Shimadzu, Tokyo, JP). Filtered water samples were acidified with 20% phosphoric acid and purged for five minutes with the instrument's carrier gas, zero air or oxygen, to remove dissolved inorganic carbon prior to injection for DOC determination. All determinations were corrected for system blank, estimated daily by regressing the results of low concentration standards (0, 2, 5 mg C L^{-1}) analysed as samples, against their 'true' value. The system blank corrects for a combination of blank sources internal to the instruments and also residual carbon in the reagent water used to make the standards.

RESULTS

Baseflow hydrology and DOC

Over the three study seasons precipitation was lowest in 2000 and highest in 1999 (Table I). Precipitation events were relatively evenly distributed in each season (Figure 2a), however, they were all drier than the 30-year average (423 mm) for the Rivière-du-Loup region (Environment Canada, 1993).

In 1999 (pre-restoration) there was no significant difference in average seasonal water table position between the restored (−46·3 cm) and cutover sites (−49·8 cm) (Table I). In 2000, one year after restoration, the average seasonal water table position at the restored site was higher (−32·1 ± 8·5 cm) than at the cutover site (−46·3 ± 7·7 cm). In 2001, the mean water table at the

Table I. Hydrologic variables at the Bois-des-Bel peatland between 8 May and 13 October of each year (25 June to 13 October for 1999)

Year	Site	Precipitation (mm)	Water table position (cm)			Runoff (mm)	Peak Discharge (L s^{-1})
			Avg.	Min.	Max.		
			−22·7	−34·2	−14·2	n/a	n/a
1999	Cutover	370	−49·8	−77·4	−41·5	96·7	0·54
	Restored	370	−46·3	−38·5	−75·5	56·8	1·60
2000	Cutover	270	−46·3	−33·2	−67·2	103·5	2·59
	Restored	270	−32·1	−49·4	−13·1	33·4	1·13
2001	Cutover	336	−41·2	−54·4	−24·7	95·1	1·68
	Restored	336	−30·6	−65·4	3·5	23·1	1·33

Discharge values in 1999 are between 25 June and 5 October (JD = 176 to 278).
For ease of comparison of the years, rain data presented between 18 May and 5 October (JD = 138 to 278) (rain data is not available before 18 May 1999).

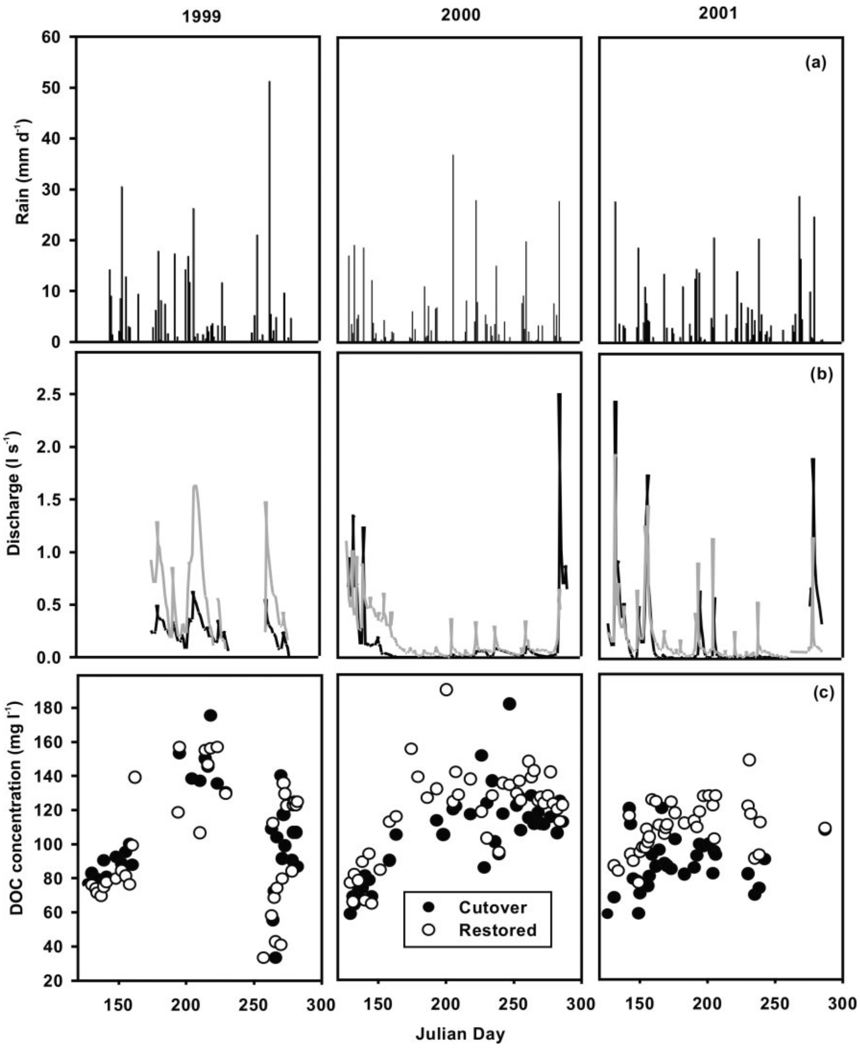

Figure 2. (a) Precipitation, (b) discharge, and (c) DOC concentration at the restored and cutover sites during the three study periods

restored site was significantly (*t*-test, $P < 0{\cdot}05$) higher ($-30{\cdot}6 \pm 15{\cdot}8$ cm) than at the cutover site ($-41{\cdot}2 \pm 7{\cdot}7$ cm).

In 1999, runoff from the restored and cutover sites was 57 and 97 mm, respectively, with maximum discharge at the cutover site (0·54 L s^{-1}) on 26 July (day 207) and at the restored site (1·60 L s^{-1}) on 29 July (day 210) (Figure 2b). The number of days when discharge was lower than 0·01 L s^{-1} was the same at both sites lasting 25 days between 22 August (day 234) and 16 September (day 259). In 2000, the year following restoration, runoff decreased at the restored site to 33·4 mm, while runoff at the cutover site increased to 103·5 mm. Discharge decreased steadily at the two sites after the spring wet-period, when the maximum peak discharge was measured at the restored site (1·13 L s^{-1}) on 9 May (day 129). Discharge increased again in the autumn when the maximum discharge at the cutover site (2·7 L s^{-1}) occurred on 12 October (day 285). The cutover site experienced 35 consecutive days between 15 June and 20 July (days 165 to 202) when average daily discharge was lower than 0·01 L s^{-1}, while the restored site experienced only three consecutive days (21–23 July, days 203 to 205) (Figure 2b). In 2001, maximum daily discharge was 1·7 and 1·3 L s^{-1} on 13 May (day 134) at the cutover and restored site, respectively, which coincided with a 27·9 mm rain event (Figure 2b). Although the cutover site had higher discharge during the wetter spring and autumn seasons, the discharge at the restored site was higher during the summer dry period, experiencing fewer days (four non-consecutive days, and three consecutive) when average daily discharge was below 0·01 L s^{-1}. The cutover site experienced 24 (18 June to 12 July, days 170 to 190) and 38 (3 August to 20 September, days 214 to 244) consecutive days when discharge was lower than 0·01 L s^{-1}. Seasonal runoff was higher at the cutover site (95·1 mm) than at the restored site (23·1 mm).

Average DOC concentration in rainwater in 2001 was $3{\cdot}5 \pm 2{\cdot}2$ mg L^{-1} and ranged from 0·9 to 8·6 mg L^{-1}. DOC concentrations were highly variable at the outflows of the restored and cutover sites over the three study seasons (Figure 2c). In general DOC increased from ~60 to 70 mg L^{-1} in early May to peak concentrations of 150 to 190 mg L^{-1} in mid-July to August and decreased to ~90 to 110 mg L^{-1} in September and October. An exception to this was observed in 1999 when the lowest DOC concentrations were measured at the outflows (36·7 and 32·2 mg L^{-1} at the restored and cutover sites respectively) on 16 September (day 250) during the largest storm event (51·2 mm) recorded during the three study seasons (Figure 2a). Maximum DOC concentrations for the three study seasons occurred in 2000 when concentrations at the restored site increased to 191·0 mg L^{-1} on 19 July (day 201) and 182·6 mg L^{-1} at the cutover site on 4 September (day 238) (Table II). In general, low DOC concentrations were observed during high flow periods in the spring and autumn, and high concentrations during the summer when discharge was low (Figure 2b,c). However, there was no significant correlation between discharge and DOC concentrations in 1999 and 2001 ($R^2 < 0{\cdot}1$), even when the data was separated into low and high discharge periods. In 2000, a weak negative correlation ($R^2 = 0{\cdot}52$) existed at the restored site but not at the cutover site.

Before restoration in the autumn of 1999, seasonal average outflow DOC concentrations were not significantly different ($P > 0{\cdot}05$) between the restored (99·4 ± 35·1 mg L^{-1}) and cutover (104·2 ± 30·4 mg L^{-1}) sites. There was no significant difference ($P > 0{\cdot}05$) between average DOC concentration at the cutover site before and after restoration (mean 107·6 ± 25·6 mg L^{-1}) in 1999 and 2000, however in 2001 DOC concentrations decreased (mean 87·5 ± 14·8 mg L^{-1}) (Table II). There was a significant ($P < 0{\cdot}05$) increase in DOC concentrations after restoration at the restored site, which remained consistently higher in 2000 (mean 119·0 ± 26·9 mg L^{-1}) and 2001 (mean 108·7 ± 15·9 mg L^{-1}) compared to values in 1999. DOC concentrations at the restored site were significantly ($P < 0{\cdot}05$) higher than that at the cutover site in both 2000 and 2001.

Snowmelt hydrology and DOC

Snow water equivalent at the restored and cutover sites was 137 and 150 mm, respectively, in mid-March, 2001. Before snowmelt, discharge from the restored and cutover sites was low (~0·05 L s^{-1}) (Figure 3a). Discharge increased during the main snowmelt period in mid April (days 101 to 115) at both sites to a peak of 16·6 and 25·1 L s^{-1} at the cutover and restored sites, respectively (Table III). The restored site returned to baseflow conditions faster than at the cutover site. Runoff for the snowmelt period was 433 and 125 mm at the cutover and restored sites, respectively. However, after the melt it was observed that the large runoff at the cutover site was due to a failed or unblocked inflow ditch in the north-east section of the cutover site.

Several open water pools formed during the snowmelt period, particularly in the southeast corner of zones 3 and 4 as well as in the depressions that were still present along the old drainage ditches. Water moved from the restored site peat fields via either the drainage ditches or along the surface and then to the outflow. Ice cover on the ponds began to break-up during the major melt event (day 113) becoming ice-free three days later.

DOC concentrations decreased with increasing discharge during the snowmelt period at the outflow of

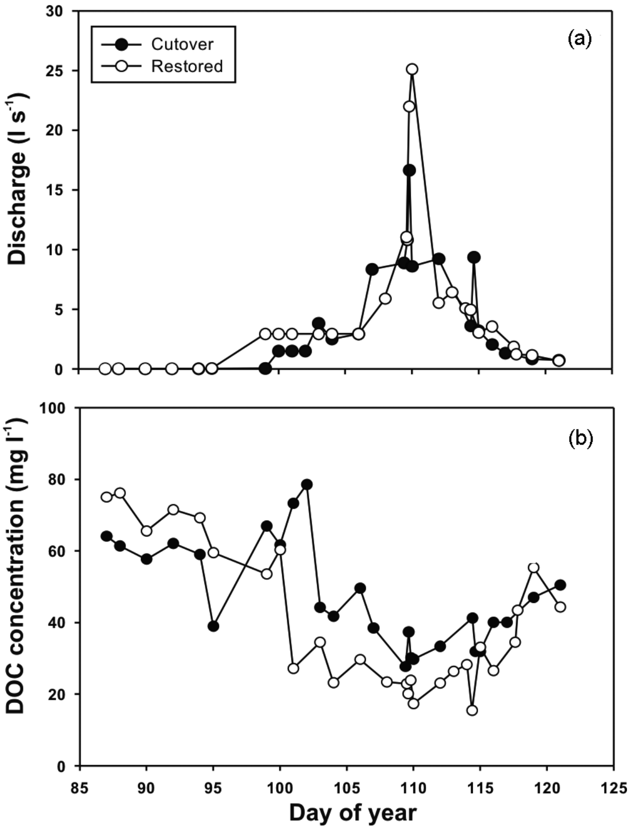

Figure 3. (a) Runoff and (b) DOC concentration for the snowmelt event. The main melt event took place between days 105 and 115 of year 2001

Table II. DOC concentrations and export at the cutover and restored natural sites for the 1999, 2000, and 2001 study periods (8 May to 13 October; 25 June to 13 October for 1999)

Year	Site	n	DOC concentration (mg L^{-1})			DOC export (g C m^{-2})
			Average	Minimum	Maximum	
1999	Cutover	38	104·2 ± 30·4	33·2	175·4	10·3
	Restored	38	99·4 ± 35·1	36·7	156·9	4·8
2000	Cutover	44	107·6 ± 25·6	58·8	182·6	8·5
	Restored	46	119·0 ± 26·9	64·9	191·0	3·4
2001	Cutover	38	87·5 ± 14·8	76·9	121·0	6·2
	Restored	39	108·7 ± 15·9	58·5	149·3	3·5

Units are mg C m^{-2}.

Table III. Hydrometric variables and DOC concentration during high flow (snowmelt and storms) events

Event	Rain (mm)	Site	Water table (cm)		Discharge ($L s^{-1}$)		DOC concentration ($mg L^{-1}$)			DOC export ($g C m^{-2}$)
			min.	max.	min.	max.	avg.	min.	max.	
Snowmelt	150[a]	Cutover	n/a	n/a	0·05	16·6	47·6	27·3	78·0	43·60
	137[a]	Restored	n/a	n/a	0·05	25·1	42·1	15·5	76·1	8·30
May 12–13	27·9	Cutover	−34·1	−21·9	0·18	2·12	58·3	54·7	61·9	0·20
		Restored	−15·5	+3·5	0·35	2·50	81·6	75·9	97·2	0·60
July 24–25	20·4	Cutover	−38·7	−33·1	0·01	0·57	91·6	76·1	97·2	0·02
		Restored	−31·0	−11·0	0·05	2·50	120·7	83·7	135·0	0·06
August 26–27	22·6	Cutover	−48·3	−37·6	0·00	0·06	82·1	66·5	94·1	0·01
		Restored	−50·4	−30·7	0·01	0·56	101·6	87·4	131·4	0·02

[a] Values indicate pre-snowmelt snow water equivalent (mm).

the two catchments. A strong negative correlation ($R^2 = 0{\cdot}76$) existed between discharge and DOC concentration at the restored site, while a weaker negative correlation existed at the cutover site ($R^2 = 0{\cdot}56$) during the snowmelt period. Before snowmelt, DOC concentrations (60 to 70 mg L^{-1}) were comparable to late summer values (Figure 3b). The average DOC concentration during the snowmelt-sampling period was $47{\cdot}6 \pm 14{\cdot}5$ and $42{\cdot}1 \pm 20{\cdot}6$ mg L^{-1} (Table III). There was no significant difference in DOC ($P < 0{\cdot}05$) between the two sites during snowmelt. Before the main melt event the DOC concentrations initially increased at the cutover site, and then decreased once discharge increased from the site. This was not observed at the restored site where DOC concentrations decreased steadily as the snowmelt began. During the high flow period of the snowmelt (days 101 to 115) water from the outflow of the cutover site had higher DOC concentration (average of 42·1 mg L^{-1}) than the restored site (average of 26·0 mg L^{-1}). The DOC concentration of the snow pack ranged from 0·9 to 1·5 mg L^{-1}.

Stormflow hydrology and DOC

The May storm event (days 132 to 133) was a 27·9 mm rain event lasting 11 h. This storm occurred early in the season, when there was still some residual ponding from snowmelt at the restored site in Zones 3 and 4. Water levels in these ponds increased during the storm and all of the drainage ditch depressions filled with water. Surface flow was observed flowing south from Zone 4 to the main collector ditch of the restored site through a pipe placed in the dyke to decrease flooding in Zone 4. At the cutover site, water collected in the drainage ditches on either side of Field 10. Discharge at the cutover site during the May storm increased from 0·18 L s^{-1} to 2·12 L s^{-1} in 9·4 h. At the restored site discharge started off higher, increasing from 0·35 L s^{-1} to 2·5 L s^{-1} in 4·8 h. The water table rose by 19 cm at the restored site to 3·5 cm above the surface (Table III), while at the cutover site the water table increased by 12·2 cm but remained below the surface (Table III). DOC concentration was not variable during the May storm event (Figure 4b). Water from the restored site had consistently higher DOC concentration ($81{\cdot}6 \pm 5{\cdot}2$ mg L^{-1}) than the cutover site ($58{\cdot}3 \pm 2{\cdot}5$ mg L^{-1}) (Table III). Higher concentrations were observed following a two-day lag after the main event.

The July storm (day 205) was a high intensity thunderstorm (peak intensity of 18·1 mm in 30 min). This storm followed a ten-day period when the total precipitation was 8·9 mm. At this time there was no open water present at the site other than the constructed pools at the restored site. Discharge at the cutover site prior to the storm was insignificant (0·006 L s^{-1}) and at the restored site it was ten times higher (0·05 L s^{-1}), but still low compared to earlier spring conditions (Figure 2b). Following the storm, discharge increased quickly at the restored site reaching the peak of 2·5 L s^{-1} in 1·2 h. At the cutover site, peak discharge (0·57 L s^{-1}) was reached in 4·3 h (Figure 4). The water table rose 5·6 cm at the cutover site and 20·0 cm at the restored site (Table III). Following the storm, water level in the ponds rose ~5 cm and water also collected in old ditch depressions at the restored site. At the cutover site water collected in the drainage ditches. Mean DOC concentration at the cutover site (Figure 4b) decreased by 19·6 mg L^{-1} while at the restored site they decreased by 44·9 mg L^{-1} (Table III) compared to pre-storm values during peak discharge. Maximum DOC concentration (97·2 mg L^{-1}) at the cutover site occurred before the storm. Concentrations returned to levels similar to pre-storm conditions approximately 6 h after the main event. DOC concentrations at the restored site increased steadily following the main event to a maximum of 135 mg L^{-1} (Figure 4b).

During the 15-day period preceding the August storm (days 238 to 239) 31·5 mm of rain fell. Water tables were low before the storm at both the cutover (−48·3 cm) and restored sites (−50·4 cm) (Table III). The only open water was in the restored site ponds. The rain event lasted 12 h during which time 22·6 mm of rain fell. Discharge at the cutover site increased from 0·002 L s^{-1} to 0·06 L s^{-1} in 7·9 h (Figure 4a). The restored site had higher discharge (0·01 L s^{-1}) before the storm, which increased to a peak of 0·56 L s^{-1} in 9·8 h (Figure 4a). Water table position rose to −37·6 and −30·7 cm at the cutover site and restored site, respectively (Table III). This lower intensity

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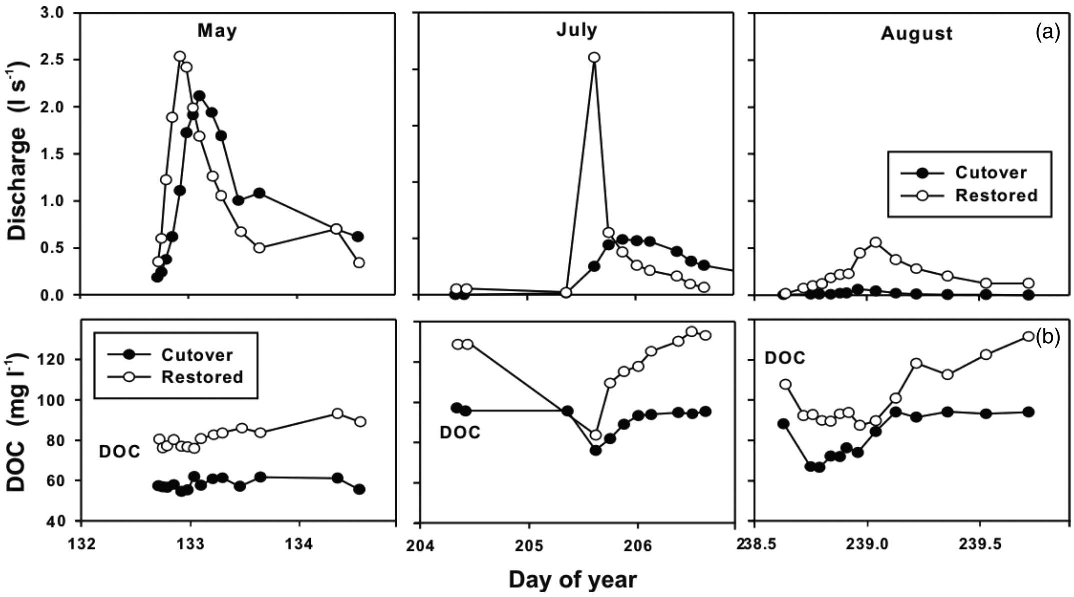

Figure 4. (a) Discharge and (b) DOC concentration during three summer storms: medium intensity storm with wet antecedent conditions in May (days 132 and 133), high intensity storm with dry antecedent conditions in July (day 205), medium intensity storm with dry antecedent conditions in August (days 238 and 239)

August storm had a similar effect on DOC concentration to the July storm except that reduced DOC concentrations occurred for a longer period following the storm (Figure 4b). On average, site discharge had higher DOC concentration ($101{\cdot}6 \pm 4{\cdot}4$ mg L^{-1}) than the cutover site ($82{\cdot}1 \pm 11{\cdot}0$ mg L^{-1}). Again minimum DOC concentrations were observed during peak discharge when DOC decreased to 66·5 and 87·4 mg L^{-1} at the cutover and restored sites, respectively. Following this dip, concentrations at the cutover site increased quickly to pre-storm concentrations (94·1 mg L^{-1}), and stayed at these levels. At the restored site a steady increase of DOC was observed following the event and DOC concentrations increased steadily to a maximum of 131·4 mg L^{-1} (Figure 4b).

DOC export

The cutover site exported more DOC than the restored site in all three study seasons. The highest exports occurred during the wettest year (1999) with cutover and restored site export of 10·3 and 4·8 g m^{-2}, respectively (Table II). In 2000, 8·5 g C m^{-2} was released from the cutover site, while the restored site released less than half that amount (3·4 g C m^{-2}). In 2001, the restored site released about the same amount of DOC as in the previous year (3·5 g C m^{-2}), while the cutover site load dropped to 6·2 g C m^{-2}. Based on rain DOC concentrations obtained in 2001, DOC input was estimated to be 1·3, 0·9, and 1·2 g C m^{-2} for the 1999, 2000, and 2001 study seasons respectively. Consequently, both sites were net exporters of DOC in all years.

DOC export for the snowmelt period at the restored and cutover site was 8·3 and 43·6 g C m^{-2} respectively. The export from the cutover site, however, is in error because the ditch was not completely blocked. DOC export for the May storm was 0·2 and 0·6 g C m^{-2} at the cutover and restored sites, respectively (Table III). Restored site DOC export was also three times that of the cutover site during the July event but the fluxes were two orders of magnitude lower. Only 0·007 to 0·02 g C m^{-2} was exported during the August event at the two sites.

DISCUSSION

Changes in DOC concentrations

Glatzel *et al*. (2002) suggested that peatland extraction would shift peat pore-waters to higher DOC concentrations and that post-extraction pore-water DOC concentrations in cutover peatlands would decrease as readily degradable carbon decreased. Moreover they stated that DOC concentrations would remain low in restored sites until new vegetation colonized it. Results from this study certainly show a large increase in pore-water DOC concentrations at cutover sites relative to natural sites, and increased decomposition due to large water table drawdowns likely causes these higher DOC concentrations. However, for the most part, the findings at the cutover and restored site do not follow the Glatzel *et al*. (2002) conceptual model. Rather, DOC concentrations at the outflows, ponds and ditches in the restored site were actually higher than the cutover site in the first two years post-restoration. The restoration process adds straw to the surface to reduce evapotranspiration. This straw is more labile than the invasive vegetation at the cutover site (Toth, 2002) and results in increased decomposition. The addition of *Sphagnum* diaspores to the peat surface and the emergence vegetation at the site also increases overall carbon quality/decomposability at the site. Moreover, water table fluctuations at the restored site are actually greater than at the cutover site (Shantz and Price, 2006) thereby enhancing decomposition. It is likely that decomposition and DOC leaching will not decrease at this site until these water table fluctuations are reduced. For this to happen a new moss layer (new acrotelm) of 20–25 cm must grow. Fresh moss has a specific yield approximately one order of magnitude higher than cutover peat.

Seasonal variations in DOC concentrations in this study were consistent with findings by other researchers (Moore, 1987; Scott *et al.*, 1999) who reported lower DOC concentrations in the spring and autumn and higher concentrations in the summer months. DOC concentrations increased during the dryer summer months when both plant and microbial activity were highest, and concentrations decreased during periods of high flow when wetter conditions resulted in higher discharge (Figure 2c). Seasonal variations are lower at the natural site than at the cutover and restored sites, where DOC concentrations increased almost two-fold.

DOC export

The construction of drainage ditches before peat extraction results in a large increase in runoff (Price, 1997) while blocking drainage ditches and creating dykes during the restoration process helped retain water following spring melt and heavy rain events (Shantz and Price, 2006), resulting in a higher average water table and lower runoff. For example, runoff decreased 84% in the first year post-restoration despite a 27% decrease in rainfall between the two study seasons. Moreover, the seasonal runoff ratio was only 2 to 3% compared to 15% before restoration. Since hydrology has a controlling influence on DOC export (Urban *et al.*, 1989; Waddington and Roulet, 1997; Fraser *et al.*, 2001) it is not surprising that these changes in the hydrologic conditions directly influenced DOC export at Bois-des-Bel as well. Despite the large decrease in runoff from blocking ditches, DOC export did not decrease as much as expected at the restored site due to the increase in DOC concentrations from enhanced leaching mentioned earlier.

The restored and cutover sites behaved similarly to natural peatlands where the largest runoff and DOC export event of the year occurred during snowmelt (Schiff *et al.*, 1997), exporting over 8 g C m^{-2}, which is about double the summer export. The hydrograph of the restored site was more responsive than that of the cutover site, likely due to wetter conditions at the two sites before freeze-up. Differences in pre-freeze-up conditions and subsequent differences in snowmelt responses also likely affected the DOC concentrations during the main melt event. During the early part of the melt, DOC concentrations increased at the cutover site to levels higher than before melting began. Towards peak runoff, DOC concentrations decreased significantly. Studies of headwater catchments have noted similar trends (Boyer *et al.*, 1997), attributing this increase to increased heterotrophic activity under the snow pack during this period.

Many studies have examined the effect of storms on the ability of soils to release DOC. Both laboratory and field experiments have demonstrated that precipitation and water fluxes are responsible for seasonal changes in DOC concentration in runoff (Kalbitz *et al.*, 2000). McDowell and Wood (1984) demonstrated that contact between water and the organic substrate can cause increased leaching followed by increased dilution of DOM once the available pool was flushed. Similar conclusions were reached by Cronan (1990), who found that DOC concentrations increased in a soil solution with longer contact time. Forest soil studies indicated that the highest DOC concentrations are reached upon rewetting following a dry period (Easthouse *et al.* 1992). Tipping *et al.* (1990) suggested that an adsorbed pool of carbon that was accumulated during the dry periods and subsequently mobilized upon re-wetting was responsible for the increased DOC observed upon moisture input. Considering these findings it was expected that the three storm events studied would present similar DOC dynamics.

Before the May storm there was limited time for DOC production since this event followed closely after the spring melt when the site was still largely saturated. Even though discharge increased ~10-fold, DOC concentrations remained similar at both sites. This suggests that both the restored and the cutover site were likely exporting DOC at their maximum potential. It also suggests that the site, in terms of DOC release, was well connected and no pools of stagnant DOC developed during this period. This is consistent with laboratory findings by Gödde *et al.* (1996) who found that sequential frequent leachings of soil samples produced DOC at a constant rate.

The July and August storms, on the other hand, occurred following dry periods when the water table was substantially lower. The increase in DOC observed at the end of this experiment indicated that the rain event created a hydrological connection with high DOC pools. The intensity of the storm events however had some effect on DOC concentration. The lower intensity August storm caused a longer and more significant increase of DOC following peak discharge, indicating that the rate of infiltration of rainwater also allowed more substantial flushing of the different DOC pools.

The pattern at the cutover site was different from that described above and the summer storms were found to have only a dilution effect on the DOC concentrations. Examining the DOC concentrations there was no evidence that during these summer rain events pools of increased DOC production were connected to the outflows. This may be a result of the dryer conditions experienced at the cutover site. Both hydrographs indicate that a large part of the rainfall is incorporated into storage rather than runoff therefore the mobilization of DOC on a larger scale was likely not possible.

Compared to the DOC export values calculated for the snowmelt period, stormflow is not a major exporter of DOC from restored and cutover peatlands. The largest DOC export during storm flow (0·6 g C m^{-2}) occurred during the spring under wetter conditions when 17 and 3% of the non-snowmelt period DOC export occurred at

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the restored and cutover sites, respectively. Contribution of the July and August storms were much less since dry conditions at the sites during this period failed to produce strong runoff responses as observed in the spring.

CONCLUSIONS

Peat extraction results in an increase in both runoff and DOC porewater concentrations and therefore DOC export from peatlands. This DOC export is largest during snowmelt and remains high many years post-peatland abandonment. Within the first few years post-restoration, DOC export is reduced by approximately one-half despite a major reduction in runoff. The high DOC export remains due to the combined effects of enhanced DOC production due to enhanced water table fluctuations and an increase in labile carbon from the addition of straw and *Sphagnum* diasporas used in the restoration process and also from emerging vegetation. We suggest that the DOC export from restored peatlands will remain high until a new surface moss layer develops that can constrain water table fluctuations.

One of the goals of peatland restoration is to reduce carbon losses from cutover peatlands. Fraser *et al.* (2001) noted that DOC can be an important component of the carbon budget of sites where gaseous carbon fluxes are low. However, at the Bois-des-Bel peatland the major carbon loss to the atmosphere is CO_2. Estimates of the CO_2 flux prior to restoration in 1999 were ~520 g C m^{-2} (Petrone *et al.*, 2001). The DOC flux before the restoration period was only 1·5% of this flux. The year after restoration CO_2 fluxes were 358 and 478 g C m^{-2} at the cutover and restored sites respectively (Petrone *et al.*, 2001). As such, the export of DOC is not important from a carbon budget perspective. However because even low concentrations of DOC have the potential to acidify natural waters of low alkalinity (Gorham *et al.*, 1986; Urban *et al.*, 1989), the downstream ecological and biogeochemical implications of the release of high concentration of DOC are great. As such we suggest that efforts should be made to restore cutover peatlands as soon as peat extraction ceases.

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REFERENCES

Atmospheric Environmental services, Canadian Climate Program, Environment Canada, Ottawa.

Boyer EW, Hornberger GM, Bencala KE, McKnight DM. 1997. Response characteristics of DOC flushing in an alpine catchment. *Hydrological Processes* **11**: 1635–1647.

Campeau S, Rochefort L. 1996. *Sphagnum* regeneration on bare peat surfaces: field and greenhouse experiments. *Journal of Applied Ecology* **33**: 599–608.

Cleary J, Roulet NT, Moore TR. 2005. Greenhouse gas emissions from Canadian peat extraction, 1990–2000: A life-cycle analysis. *Ambio* **34**: 456–461.

Cronan CS. 1990. Patterns of organic acid transport from forested watersheds to aquatic ecosystems. In *Organic Acids in Aquatic Systems*, Perdue EM, Gjessing ET (eds). John Wiley and Sons: Chichester.

Easthouse KB, Mulder J, Christophersen N, Seip M. 1992. Dissolved organic carbon fractions in soil and stream water during variable hydrological conditions at Birkenes, Southern Norway. *Water Resources Research* **28**: 1585–1596.

Environment Canada. 1993. *Canadian Climate Normals, 1961–1990. Québec*.

Fraser CJD, Roulet NT, Moore TR. 2001. Hydrology and dissolved organic carbon biogeochemistry in a large peatland. *Hydrological Processes* **15**: 3151–3166.

Glatzel s, Kalbitz K, Dalva M, Moore T. 2002. Dissolved organic matter properties and their relationship to carbon dioxide efflux from restored peat bogs. *Geoderma* **113**: 397–411.

Gödde M, David MB, Christ MJ, Kaupenjohann M, Vance GF. 1996. Carbon mobilization from the forest floor under red spruce in the northeastern U.S.A. *Soil Biology and Biochemistry* **28**: 1181–1189.

Gorham E. 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. *Ecological Applications* **1**: 182–195.

Gorham E, Underwood JK, Martin FB, Ogden JG. 1986. Natural and anthropogenic causes of lake acidification in Nova Scotia. *Nature* **324**: 451–453.

Heathwaite AL. 1995. The impact of disturbance on mire hydrology. In *Hydrology and Hydrochemistry of British Wetlands*. John Wiley & Sons Ltd; 401–417.

Kalbitz K, Solinger S, Park JH, Michalzik B, Matzner E. 2000. Controls on the dynamics of dissolved organic matter in soils: A review. *Soil Science* **165**: 277–304.

McDowell WH, Wood T. 1984. Soil processes control dissolved organic carbon concentration in stream water. *Soil sciences* **137**: 23–32.

Moore TR. 1987. Patterns of dissolved organic matter in subarctic peatlands. *Earth Surface Processes and Landforms* **12**: 387–397.

Petrone RM, Waddington JM, Price JS. 2001. Ecosystem scale evapotranspiration and net CO_2 exchange from a restored peatland. *Hydrological Processes* **15**: 2839–2845.

Price JS. 1997. Soil moisture, water tension, and water table relationship in a managed cutover bog. *Journal of Hydrology* **202**: 21–32.

Price JS, Rochefort L, Quinty F. 1998. Energy and moisture considerations on cutover peatlands: surface microtopography, mulch cover and *Sphagnum* regeneration. *Ecological Engineering* **10**: 293–312.

Price JS2007Aug23 072334, Whitehead GS. 2001. Developing hydrological thresholds for *Sphagnum* recolonization on an abandoned cutover bog. *Wetlands*: 32–42.

Rochefort L, Malterer T, Quinty F, Campeau S, Johnson K. 2003. North American approach to the restoration of *Sphagnum* dominated peatlands. *Wetlands Ecology and Management* **11**: 3–20.

Schiff SL, Arawena R, Trumbore SE, Hinton MJ, Elgood R, Dillon PJ. 1997. Export of DOC from forested catchments on the Precambrian Shield of Central Ontario: clues from ^{13}C and ^{14}C. *Biogeochemistry* **36**: 42–65.

Scott KJ, Kelly CA, Rudd JWM. 1999. The importance of floating peat to methane fluxes from flooded peatlands. *Biogeochemistry* **47**: 187–202.

Schlotzhauer SM, Price JS. 1999. Soil water flow dynamics in a managed cutover peat field, Québec: Field and laboratory investigations. *Water Resources Research* **35**: 3675–3683.

Shantz MA, Price JS. 2006. Characterization of surface storage and runoff patterns following peatland restoration, Québec, Canada. *Hydrological Processes* **20**: 3799–3814.

Thurman EM. 1985. *Organic Geochemistry of Natural Waters*. Martinus Nijhoff/Dr W. Junk Publishers: Dordrecht.

Tipping E. 1981. The adsorption of aquatic humic substances by iron oxides. *Geochemica et Cosmochemica Acta* **45**: 191–199.

Tipping E, Reddy MM, Hurley MA. 1990. Modeling electrostatic and heterogeneity effects on proton dissociation from humic substances. *Environmental science and Technology* **24**: 1700–1705.

Tóth K. 2002. *Dissolved organic carbon dynamics in a cutover and restored peatland.* MSc thesis, McMaster University.

Tuittila E-S, Komulainen V-M, Vasander H, Laine J. 1999. Restored cut-away peatland as a sink for atmospheric CO_2. *Oecologia* **120**: 563–574.

Urban NR, Bayley SE, Eisenreich SJ. 1989. Export of dissolved organic carbon and acidity from peatlands. *Water Resources Research* **25**: 1619–1628.

Van Seters TE, Price JS. 2001. The impact of peat harvesting and natural regeneration on the water balance of an abandoned cutover bog, Québec. *Hydrological Processes* **15**: 233–248.
Waddington JM, Roulet NT. 1997. Groundwater flow and dissolved carbon movement in a boreal peatland. *Journal of Hydrology* **191**: 122–138.
Waddington JM, Price JS. 2000. Effect of peatland drainage, harvesting and restoration on atmospheric water and carbon exchange. *Physical Geography* **21**: 433–451.
Waddington JM, Warner KD, Kennedy GW. 2002. Cutover peatlands: a persistent source of atmospheric CO_2. *Global Biogeochemical Cycles* **16**(1): 1002. DOI: 10.1029/2001GB001398.
Wind-Mulder HL, Rochefort L, Vitt DH. 1996. Water and peat chemistry comparison of natural and post-harvested peatlands across Canada and their relevance to peatland restoration. *Ecological Engineering* **7**: 161–181.