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Gaseous carbon dioxide and methane, as well as dissolved organic carbon losses from a small temperate wetland under a changing climate

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"Capsule": *The export of dissolved organic carbon from wetlands is projected to double by 2050 under climate change scenarios and increases in atmospheric carbon dioxide.*

Abstract

Temperate forests can contain large numbers of wetlands located in areas of low relief and poor drainage. These wetlands can make a large contribution to the dissolved organic carbon (DOC) load of streams and rivers draining the forests, as well as the exchange of methane (CH_4) and carbon dioxide (CO_2) with the atmosphere. We studied the carbon budget of a small wetland, located in Kejimkujik National Park, Nova Scotia, Canada. The study wetland was the Pine Marten Brook site, a poor fen draining a mixed hardwood-softwood forest. We studied the loss of DOC from the wetland via the outlet stream from 1990 to 1999 and related this to climatic and hydrologic variables. We added the DOC export information to information from a previously published model describing CH_4 and CO_2 fluxes from the wetland as a function of precipitation and temperature, and generated a new synthesis of the major C losses from the wetland. We show that current annual C losses from this wetland amount to 0.6% of its total C mass. We then predicted that under climate changes caused by a doubling of atmospheric CO_2 expected between 2040 and 2050, total C loss from the wetland will almost double to 1.1% of total biomass. This may convert this wetland from what we assume is currently a passive C storage area to an active source of greenhouse gases. Crown Copyright © 2001 Published by Elsevier Science Ltd. All rights reserved.

Keywords: Wetlands; CH_4; CO_2; DOC; Water tables; Climate change

1. Introduction

Wetlands have a key role in controlling the terrestrial carbon cycle (Matthews and Fung, 1987) as they have the ability to sequester atmospheric carbon into peat. Northern peatlands for example, contain approximately 500×10^{15} g of C (Gorham, 1991) and thus are a major global sink. Though wetlands have acted as sinks since the last glaciation, by incorporation of C into accumulating peat and organic matter, they also release C back into the atmosphere over time. The main sources of loss are: as CO_2 from plant respiration and aerobic peat decomposition; CH_4 from the anaerobic decomposition of peat; and as dissolved organic carbon (DOC) from the steeping of soil organic matter in water (Fig. 1; Clair et al., 1999). Dissolved inorganic C (DIC) is also lost in waters draining wetlands, but will not be addressed in this work for reasons that will be discussed here.

The relative importance of the C losses, especially in response to a changing climate, are poorly known (Moore et al., 1998; Dalva et al., 2001). The main control on a wetland's ability to retain carbon and to generate CH_4 and DOC, is determined in large part by its ability to remain wet, as peat is maintained under anaerobic conditions. Shifts in seasonal hydrology caused by a changing climate should therefore have measurable impacts on the accumulation or loss of organic carbon from wetland soils. We felt it useful to assess how hydrological changes caused by a changing climate, could affect the main C losses from wetlands in a humid, cool, temperate growing area.

The purpose of this work was therefore to produce a picture of current annual carbon losses from a well-defined wetland located in Nova Scotia, Canada, and to compare this loss with the total C currently stored in peat. We use data on CO_2 and CH_4 fluxes from this wetland which we reported elsewhere. We then add new information about aquatic DOC losses and the total C content of the peat, to provide a new synthesis of a

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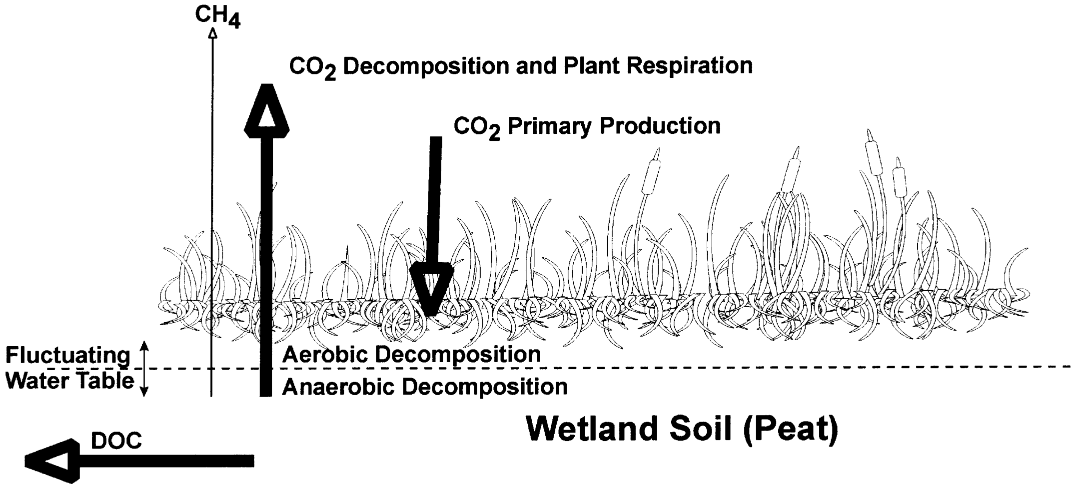

Fig. 1. Simplified view of the wetland carbon cycle used in this study.

C budget for the wetland. We then use other models also developed elsewhere that predict changes in gaseous and aquatic C losses under different climatic scenarios and apply it to the site. This then allows us to calculate how a X2 CO_2 change in climate predicted for this region should affect the annual C losses from the peatland and compare these data to the current situation.

2. Materials and methods

The study site was located in Kejimkujik National Park, approximately 60 km from both the Atlantic Ocean and the Bay of Fundy in eastern Canada (Fig. 2). Mean annual precipitation (1967–1993) is 1403 mm, of which approximately 57% occurs from November to May (Table 1). Annual average temperature is 6.3 °C, while the May–November mean is 12.2 °C.

We selected a small wetland, the Upper Pine Marten Brook that has well defined boundaries, and a well defined outlet stream (Fig. 2) as the study site. The wetland was 1.6 ha in area and was located in a steep-sided 12.4 ha basin composed mostly of a mixed hardwood-softwood forest. The basin bedrock was mostly slate which allowed little groundwater input. The dominant wetlands plants were *Sphagnum centrale, S. imbricatum, S. fallax, S. flexuosum, S. magellanicum* and *S. torreyanum* which together accounted for approximately 50% of total ground cover. The remainder of the wetland groundcover was comprised of *Calamogrostis canadensis, Dulichium ardinaceum* and the overstory consisted of alder (*Alnus* spp.), balsam fir (*Abies balsamea*) and white spruce (*Picea glauca*). Sampling sites were selected to take into account the various types of wetland plant communities found. These also usually reflected differences in average depth to the water table. This type of poor fen is quite common in much of mainland Nova Scotia (Davis and Browne, 1997).

To measure gas fluxes in the wetland, we sampled 18 sites with permanently installed 25-cm diameter collars along four transects containing variations in microtopography and hydrological conditions (Dalva et al., 2001). Most replicate sampling sites were placed along stream bank and pool areas as these generally showed the highest and most variable gas fluxes, particularly for CH_4. A system of boardwalks was constructed in the second year of the study to all sampling sites to allow access without disturbing the peat surface. Fluxes were measured by determining changes in headspace concentration of the gases within a 18 l polycarbonate chamber placed on the collar. The chamber was covered with aluminum foil to minimize heating. CO_2 emission rates therefore reflected total heterotrophic and autotrophic emissions from soil and plants. Gas sampling and analysis details are found in (Dalva et al., 2001). We collected peat cores at each of the collar sites and estimated the mean peat depth in the wetland to be 1 m with an average C mass of 40 kg m^{-2}.

We developed a model linking changes in wetland CO_2 and CH_4 emission, to the aspatial forest hydrology model ForHyM2 (*For*est *Hy*drology *M*odel *2* (Meng et al., 1995) to estimate and predict the growing season soil moisture and temperature, and the average level of the water table as it would change in the wetlands from day to day. Model input was restricted to daily meteorological data (snow, rain, mean daily air temperature, daily solar radiation), and to average soil and canopy conditions. An Environment Canada weather station, located 500 m from the Pine Martin Brook basin, provided weather data from 1966 to 1998.

Dalva et al. (2001) modeled regional soil moisture and temperature, and average water table levels were regressed against wetland CH_4 and CO_2 fluxes averaged over all sites providing a wetland-wide estimate of gaseous losses. In so doing, regional upland soil conditions were used as proxies for estimating the corresponding

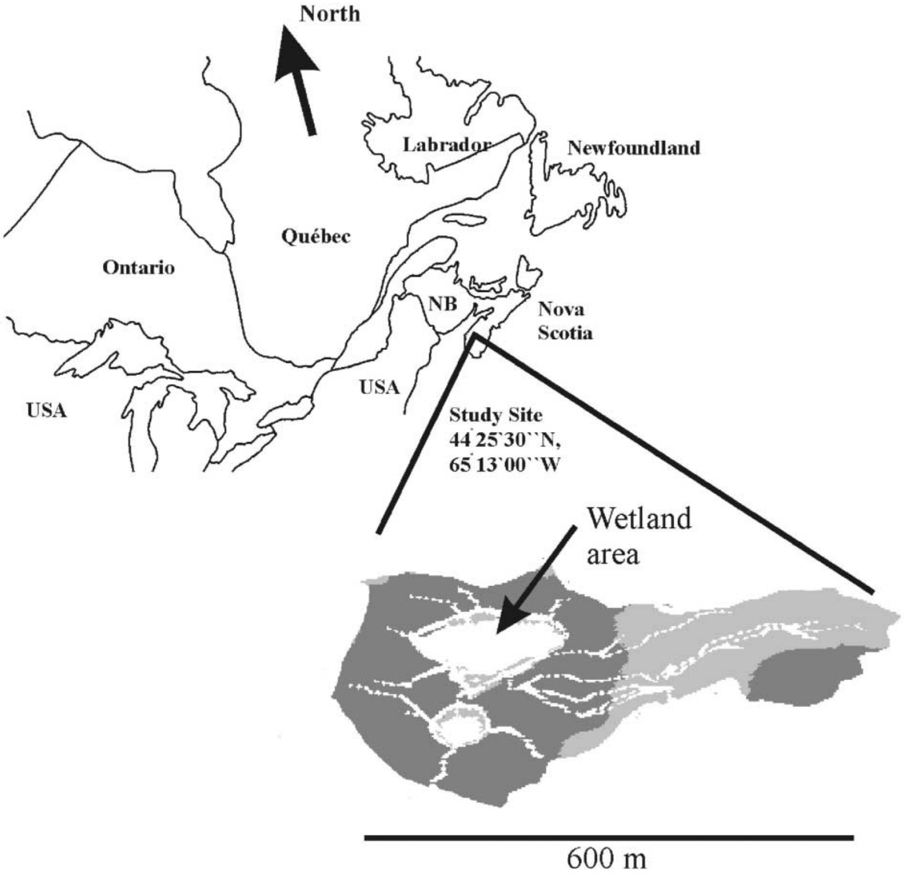

Fig. 2. Geographical location of the study site along with its specific basin outline.

Table 1
Current and X2 CO_2 estimated methane and carbon dioxide losses from the Pine Marten wetland[a]

	Current		X2 CO_2 estimated	
	CH_4 (g m^{-2})	CO_2 (g m^{-2})	CH_4 (g m^{-2})	CO_2 (g m^{-2})
1992	1.96	166.49	5.46	375.77
1993	2.49	220.07	6.24	399.30
1994	3.16	185.40	7.84	392.00
1995	2.70	253.20	6.77	405.96
1996	2.50	182.14	6.57	298.37
1997	2.77	256.23	7.23	430.18
1998	6.87	375.78	14.09	537.89
Mean	2.59	210.59	7.74	405.64
S.D.	0.39	38.41	2.90	71.55023

[a] Current 1996 and 1997 are measured and the remaining years are model results.

moisture and temperature variations within the wetlands. The resulting regression equations were subsequently built into the ForHyM2 model, to calculate daily CH_4 and CO_2 fluxes as outlined.

We applied the equations to the winter period at the site even though the model was not validated for this period. CH_4 and CO_2 values were generated for the winter season, even though they are difficult to measure due to the effect of the soil frost layer as well as snow cover. We felt it useful to try to see what the magnitude of these losses could be. The values that we calculated in this case were not large, and as they did not affect the overall flux magnitudes, we felt comfortable in using them, if only for illustrative purposes. We do understand however, that the estimated winter values are provisional and need to be better quantified in order to provide greater assurance in the results.

The stream draining the wetland was also sampled daily for 1992 and 1993 and analyzed for dissolved organic carbon. Samples were collected weekly from 1994 to 1998. Days where sampling was missed were filled in by interpolation. These values were combined with daily runoff values calculated for the Kejimkujik Park region by the ForHyM2 model to estimate daily, weekly and seasonal exports from the basin. We assume in this case that most of the DOC was produced by the wetland and that the forested basin contribution was minimal. This assumption is not unreasonable based on the literature. For example, Moore (1989) showed that organic debris from stream channels was the most important contributor to DOC in forested and disturbed catchments in New Zealand streams. Mulholland (1997) also showed that most DOC measured in streams originated within a few tens of meters from the stream channel itself. For these reasons, as a first approximation, we are assuming that the small basin surrounding the wetland had little influence on the wetland stream DOC export.

We decided not to include aquatic DIC losses from the wetland for a number of reasons. First, there was no basin contribution due to the slate bedrock. We also made the simplistic assumption that all CO_2 generated by plant decomposition was released in gaseous form through the peat surface. For our purpose, this assumption is not unreasonable, especially as the water chemistry did not favor the retention of CO_2 generated by plant decomposition. Stream pH rarely exceeded a value of 6.0, and the mean volume-weighed pH at the site was 4.8 (Clair et al., 2001). At these low pH values, most of the DIC will be as H_2CO_3* which should be in equilibrium with atmospheric CO_2 (Stumm and Morgan, 1996) and thus say more about the carbon dioxide cycle in stream water than about the carbon in the wetland it emerged from. This assumption is not completely correct, as CO_2 is usually supersaturated in stream waters due to plant decomposition and delayed equilibrium reactions. However, direct DIC measurements that we have done over the last 2 years show us that DIC values are approximately 10% of DOC and as will be shown, are therefore quite low compared to the rest of the C budget.

We extracted the 1992–1998 daily weather data and modified these by the monthly changes predicted by the Canadian Climate Centre General Circulation Model II (CCC GCMII; Boer et al., 1992) for the X2 CO_2 scenario for the period of May–November. For this part of Nova Scotia, the model predicted temperature changes of +3° for May, August, September, October and November, and +4° for the winter months and June and July. Precipitation was predicted to decrease by −5% in May, August and November, and 15% in June, increase by 10% in the winter and show no change in July, September and October.

We calculated the possible change in DOC losses to the stream under a X2 CO_2 atmosphere by using the approach developed by (Clair et al., 1999) for this region of Canada. The method involved using a neural network approach to relate the current relationship between climate and geographical variables and DOC exports. The developed model was then used to predict how climatic changes calculated for the area might change DOC exports.

3. Results and discussion

Gaseous CH_4 and CO_2 losses from the wetland followed a seasonal pattern (Fig. 3; Dalva et al., 2001), but one shifted by several months compared to the DOC. The greatest losses of both gases occurred in the warm summer months, with decreasing losses under the cooler spring and fall periods. A summary of the the annual losses (Table 1) shows that large year to year variations can occur, also driven by growing season temperatures and precipitation. In general, cooler, wetter conditions will lead to lower losses of both gases, while warmer, drier conditions lead to greater losses. CO_2 losses were approximately 100 times those of CH_4 and 10 times that of DOC.

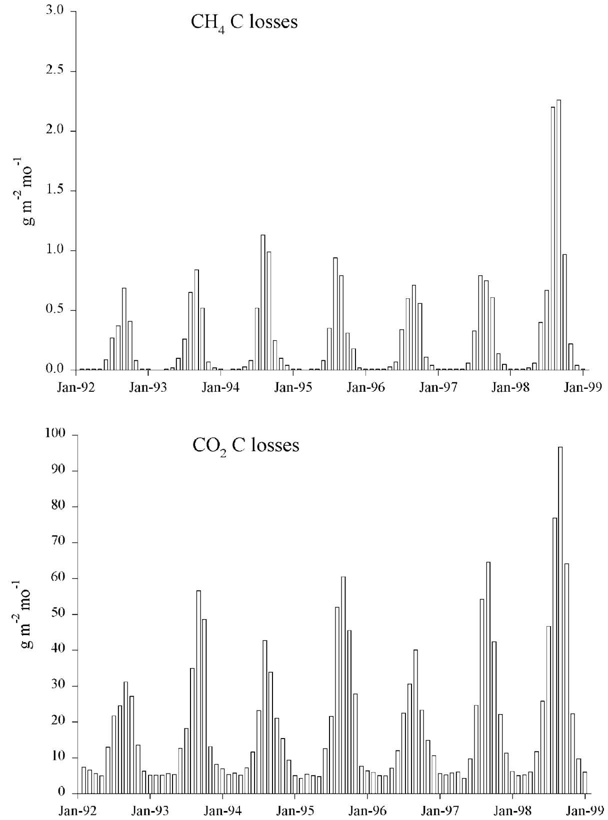

Fig. 3. Monthly CH_4 and CO_2 losses from the site from 1992 to 1999 (adapted from Dalva et al., 2001).

When we applied the changes in climate predicted in the future to the 1992-1998 data, we predicted a large increase in the losses of both CH_4 and CO_2 for the wetland (Table 1). Our model predicts that a greater than doubling of CH_4 and slightly less than doubling of CO_2. The greater loss of CH_4 was somewhat surprising, as summers will be drier and thus the water table will be drawn down further and anaerobic decomposition should be less. However, the model seems to suggest early summer anaerobic decomposition under warmer conditions should more than make up for the drawdown in the water table. We expected CO_2 production to increase in the wetland due to greater plant and root respiration as well as greater decomposition of peat under drier conditions.

Daily DOC exports followed a seasonal cycle controlled mainly by runoff (Fig. 4). Though DOC concentrations are usually greatest in the summer, the water flows were so low as to make total exports during

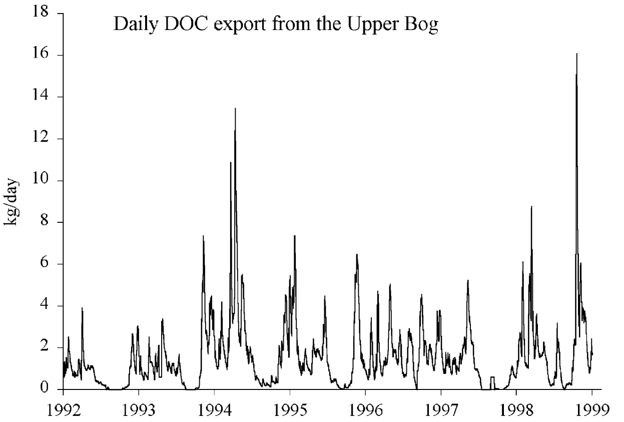

Fig. 4. Daily DOC losses from the study basin.

that period, a minor part of the total annual loss. There was a great deal of year-to-year variability in DOC exports (Table 2), driven mostly by annual differences in spring runoff and winter runoff events. On average however, the wetland exported 36 g DOC m^{-2} $year^{-1}$, with a 12 g m^{-2} $year^{-1}$ standard deviation.

The CCC GCM II predictions for the X2 CO_2 atmosphere at Kejimkujik predict warmer and drier summers in the future, but wetter winters and springs. Our work predicts that under this global warming scenario, there will be an increase of approximately 20% of DOC export over current levels if this proposed state is reached. This will occur mostly because of increased runoff volume and intensity in the winter and spring in this region (Clair et al., 1998).

We then used the current (measured) gaseous and aquatic C flux data and compared them to the current wetland C biomass to allow us to assess the proportion of the wetland that is lost to both the atmosphere and the stream each year. We then also compared the gaseous and water C losses predicted under 2X CO_2 atmosphere to the current C biomass. Our objective was to see whether the increased C losses through gaseous flux and water export under a warmer atmosphere would be significantly different from those of present conditions.

We estimated that under current atmospheric conditions, 0.6% of the total peat C is lost annually to respiration and DOC export (Table 3). Under a X2 CO_2 regime, the annual percent C loss would most likely be 1.1% of the total, roughly double the current conditions. As a first approximation, if we assume that the wetland is in an equilibrium between C losses and NPP, then in order to maintain the current wetland at a stable level, net annual primary productivity has to equal 0.6% of the total peat content.

Under a warmer scenario, our predictions suggest that NPP would have to roughly double from current levels to maintain current peat depth and C composition. If the wetland's NPP is not doubled within the next 50 years when we expect to reach the 2X CO_2 atmosphere, it is therefore likely that this wetland will become an active source of greenhouse C. As this wetland is a *Sphagum* dominated system, thus suggesting poor nutrient availability, we feel that it is quite likely that C loss will be significantly be greater than C incorporation.

Table 2
Annual total and area normalized DOC exports from the Upper Pine Marten wetland

Year	Current		X2 CO_2 estimated	
	Total (kg)	g m^{-2}	Total (kg)	g m^{-2}
1992	280.8	17.6	351.7	22.1
1993	492.4	31.0	537.4	33.8
1994	794.4	50.0	979.6	61.7
1995	615.2	38.7	757.0	47.6
1996	671.2	42.2	741.1	46.6
1997	350.9	22.1	448.9	28.2
1998	795.9	50.1	932.2	58.7
Avg	571.6	36.00	678.3	42.7
S.D.	189.4	11.9	221.9	13.9

Table 3
Average sum of carbon losses between 1992 and 1998 at Pine Marten wetland, as well as under a X2 CO_2 predicted atmosphere compared to the average total peat C content

Compartment	Current (g m^{-2})	2X CO_2 (g m^{-2})
CO_2	210.6	405.6
CH_4	2.6	7.7
DOC	36.0	42.7
Total loss	249.2	456.0
% of total peat	0.6%	1.1%

4. Conclusions

Results from our study show that annual C losses from a small, nutrient-poor temperate wetland are currently 0.6% of the total C stored in biomass. The change in climate predicted for this region should double this C loss over the next 50 years due to drier summer conditions which are not conducive to maintenance of the peat depth due to a lowering of the water table and thus an increase in CO_2 production. Greater spring runoff will also increase the DOC losses from the wetland.

We should note though that our measured losses through water are probably underestimates, as we did not include DIC exports. However, considering the acidity of the water, any estimate we provided would not tell us much about organic C breakdown. Instead, it would be more an indication of water–air exchange processes that occur in the outlet stream. Nevertheless, we must realize that our estimate of C loss through the stream is an underestimate, though its magnitude is probably approximately relatively low compared to the

DOC contribution. More work clearly needs to be done to better understand this portion of the wetland's C cycle.

Another shortcoming to the data that we were forced to accept, were the winter CO_2 and CH_4 flux estimates. Frozen ground and insulation of the wetland surface by the snowpack make this a very different system when it comes to gas flux mechanisms. Few winter flux data exist in the literature, as they require different measurement approaches, such as the gas diffusion calculation used by Wickland et al. (2001). We suspect that our estimates are probably low compared to real values, which may make our C loss values somewhat conservative.

Overall though, we feel that this study and its long-term conclusions quite reasonably describes the current and future situations in most nutrient-poor wetlands in Nova Scotia, and most likely in the adjacent areas of northern Maine, USA and much of New Brunswick, Canada. However, these quantitative results probably do not apply to nutrient-rich wetlands, nor to sites further north where hydrological changes will be different. An estimation of whether North American wetlands overall change to greater sources or sinks of C in the future will require an understanding of precipitation and temperature changes which will occur in all of the continent's ecoclimatic zones. It will also require the incorporation of wetland types as well as general topographical constraints. Only with this information in hand, will a reasonable estimate of wetland contribution to the global C cycle be possible as the planet's climate changes. Studies such as these are thus needed to address the uncertainties in C peatland changes that were addressed by Moore et al. (1998).

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References

Boer, G.J., McFarlane, N.A., Lazare, M., 1992. Greenhouse gas-induced climate change simulated with the CCC second-generation general circulation model. J. Climate 5, 1045–1077.

Clair, T.A., Ehrman, J.M., Higuchi, K., 1998. Changes to the runoff of Canadian Ecozones under a doubled CO_2 atmosphere. Can. J. Fish. Aquat. Sci. 55, 2464–2477.

Clair, T.A., Ehrman, J.M., Higuchi, K., 1999. Changes in freshwater carbon exports from Canadian terrestrial basins to lakes and estuaries under a $2xCO_2$ atmospheric scenario. Global Biogeochem. Cycles 13, 1091–1097.

Clair, T.A., Bobba, A.G., Miller, K., 2001. Yearly changes in the seasonal frequency and duration of short-term acid pulses in some Nova Scotia, Canada, streams. Environ. Geol. 40, 582–591.

Dalva, M., Arp, P., Moore, T.R., Clair, T.A., 2001. Methane and carbon dioxode emissions from wetlands, Kejimkujik National Park, Nova Scotia: measurements, predictions and climate change. J. Geophys. Res.-Atmos. 106, 2955–2962.

Davis, D.S., Browne, S.H. (Eds.), 1997. The Natural History of Nova Scotia, Vol. 1. Topics and Habitats. Nimbus Publishing, Halifax, Nova Scotia, Canada.

Gorham, E., 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. Ecol. Appli. 1, 182–195.

Matthews, E., Fung, I., 1987. Methane emission from natural wetlands: global distribution, area, and environmental characteristics of sources. Global Biogeochem. Cycles 1, 61–86.

Meng, F.-R., Bourque, C.P.A., Jewett, K., Daugharty, D., Arp, P.A., 1995. The Nashwaak experimental watershed project: analysing effects of clearcutting on soil temperature, soil moisture, snowpack, snowmelt and stream flow. Water, Air, Soil Pollut. 82, 363–374.

Moore, T.R., 1989. Dynamics of dissolved organic carbon in forested and disturbed catchments, Westland, New Zealand 1. Maimai. Water Resour. Res. 25, 1321–1330.

Moore, T.R., Roulet, N.T., Waddington, J.M., 1998. Uncertainty in predicting the effect of climatic change on the carbon cycle of Canadian peatlands. Clim. Change 40, 229–246.

Mulholland, P.J., 1997. Dissolved organic matter concentration and flux in streams. J. North Amer. Benthol. Soc. 16, 131–141.

Stumm, W., Morgan, J.J., 1996. Aquatic Chemistry: Chemical Equilibria and Rates in Natural Waters, 3rd Edition. John Wiley, NY.

Wickland, K.P., Striegl, R.G., Mast, M.A., Clow, D.W., 2001. Carbon gas exchange at a southern Rocky Mountain wetland, 1996–1998. Global Biogeochem. Cycles 15, 321–335.