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Northern fens: methane flux and climatic change

By NIGEL ROULET[1], TIM MOORE[2], JILL BUBIER[2] and PETER LAFLEUR[3], [1]*Department of Geography, York University, 4700 Keele St., North York, Ontario, Canada M3J 1P3*; [2]*Department of Geography, McGill University, 805 Sherbrooke St. W., Montreal, Quebec, Canada H3A 2K6*; [3]*Department of Geography, Trent University, Peterborough, Ontario, Canada K9J 7B8*

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ABSTRACT

Methane flux from northern peatlands is believed to be an important contribution to the global methane budget. High latitude regions are predicted to experience significant changes in surface temperature and precipitation associated with the $2 \times CO_2$ climate scenarios, but the effects of these changes on methane emission are poorly understood. A peatland hydrologic model predicted June–August decreases in water storage of between 82 and 144 mm, using as inputs increases in temperatures of 3°C and rainfall of 1 mm d^{-1}. These changes translate into a water table drop, relative to the peat surface, of between 14 and 22 cm, depending on whether the fen has a floating or non-floating surface. The 3°C air temperature increase was predicted to raise peat temperature at 10 cm depth by 0.8°C. These changes were then applied to relationships derived at a subarctic fen for water table: methane flux: temperature at 10 cm depth. Increased temperatures raise the methane flux by between 5 and 40%, but the lowered water table decreases methane flux by 74 and 81%, at the floating and non-floating fen sites, respectively. These results suggest that methane emissions from northern peatlands are more sensitive to changes in moisture regime than temperature within the range of changes predicted for $2 \times CO_2$ scenarios.

1. Introduction

The concentration of atmospheric methane is increasing at approximately 13 ppbv yr^{-1}, or 1% (Cicerone and Oremland, 1988; Khalil et al., 1989). Methane is a radiatively and chemically active trace gas, which is believed to contribute about 12% of the calculated increase in global warming, associated with changes in atmospheric composition (Hansen et al., 1989). The estimated annual global emission of methane is about 540 Tg yr^{-1}, of which between 80 and 110 Tg yr^{-1} may be produced from wetlands (Aselmann and Crutzen, 1989; Cicerone and Oremland, 1988; Matthews and Fung, 1987).

Mid- to high-latitude regions contain the largest area of wetlands, particularly latitudes between 50 and 70°N (Aselmann and Crutzen, 1989). Measurements of methane flux from northern boreal and subarctic wetlands reveal that annual emission rates can range from <0.5 to >10 g $CH_4 \text{ m}^{-2} \text{ yr}^{-1}$ (e.g., Crill et al., 1988; Moore and Knowles, 1987, 1990; Moore et al., 1990; Sebacher et al., 1986; Svensson, 1980; Whalen and Reeburgh, 1988). Major controls on these emission rates are temperature, water table position and soil and plants, as they influence the microbiological processes of methane production and oxidation.

Mid- to high-latitude regions of the northern hemisphere are also those areas that are predicted to exhibit the largest changes in surface temperature and precipitation, under general circulation model predictions associated with a doubling of the atmospheric carbon dioxide concentration (e.g., Mitchell, 1989). This raises the question of what will be the methane emission response of these northern wetlands to climatic change. Several authors have predicted or assumed that increased air temperatures will produce an increase in methane emission rates (e.g., Hameed and Cess, 1983; Khalil and Rasmussen, 1989; Lashof, 1989; Prinn, 1990). However, a fall in the position of the water table in the wetlands would be a response to increased rates of evapotransiration, and this could produce a decrease in methane emission rates (e.g., Moore and Knowles, 1989).

In this paper, we examine the possible direction and magnitude of change of methane flux from northern wetlands. We use predicted changes in surface temperature and precipitation from a $2 \times CO_2$ climate scenario (Mitchell, 1989) to estimate changes in peat temperature and water table position, for floating and non-floating northern fens. We then apply our knowledge of the relationships between methane emissions and temperature and water table position for a subarctic fen near Schefferville (Moore et al., 1990) to predict the change in methane flux.

2. Methods

A simple hydrological model for peatlands was used to predict water table position (Roulet, 1991). The model solves for the changes in water storage based on the water balance:

$$\delta S/\mathrm{d}t = r - E_t \pm F$$

where r is rainfall, E_t is evapotranspiration, estimated using the Penman-Monteith equation (Lafleur and Rouse, 1988), F is lateral and subsurface flow, assumed in this study to equal 0.

From $\delta S/\mathrm{d}t$, the position of the water table was calculated:

$$\delta WT/\mathrm{d}t = (1/S_y)\, \delta S/\mathrm{d}t - \beta(1/S_y)\, \delta S/\mathrm{d}t,$$

where β is the buoyancy adjustment factor used for floating fens ($\beta = 0$ for fixed surfaces; $0 < \beta < 1$ for floating sufaces), and S_y is the specific yield of peat.

The model was run using the mean June, July and August temperature, relative humidity, wind speed and total precipitation for 5 locations in the northern boreal/subarctic region of Canada. The change in water storage was computed from the difference between this model run and that calculated in a second run, in which the monthly temperature and daily precipitation were increased 3°C and 1 mm, respectively, similar to the changes predicted from the $2 \times CO_2$ scenarios (Mitchell, 1989). In this approach, we are assuming that the fens are infinitely large, so that all moisture exchange that affects storage is vertical.

In the second run, it was assumed that evapotranspiration would continue at a rate sufficient to sustain current relative humidity levels. Empirical relationships between air temperature and vapour pressure deficit from several northern wetlands (Lafleur and Rouse, 1988) suggest that relative humidity would decrease greater than that predicted by the saturation vapour pressure curve and increasing temperatures, for temperatures above 15°C. Maintaining constant relative humidity ensures that evapotranspiration is increased conservatively. Bulk surface resistance for non-floating, sedge-covered fens was held constant at $100\ \mathrm{s\ m^{-1}}$ and set at $0\ \mathrm{s\ m^{-1}}$ for floating fens (Lafleur, 1988; Lafleur and Rouse, 1988; Roulet, 1991). At present, this model is only applicable to fens, as the appropriate canopy resistances have yet to be determined for bogs with non-vascular plants. Aerodynamic resistance was calculated from wind speed and a surface roughness for fens (Lafleur and Rouse, 1988). Net radiation was obtained from the Atmospheric Environment Service of Canada records (Atmospheric Environment Service, 1989). Ground heat flux was assumed a constant 10% of net radiation.

A linear regression between air temperature and peat temperature at a 10 cm depth was used to predict changes in peat temperature associated with the 3°C increase in air temperatures (Moore and Knowles, 1990).

Relationships between methane emission and peat temperature and water table position for a northern fen near Schefferville were used to estimate the response of methane emissions to changes in temperature and water table (Moore and Knowles, 1990; Moore et al., 1990).

3. Results and discussion

The hydrological model was run on climatic data collected from locations across northern boreal/subarctic Canada (Table 1). The model predicted an average change in summer soil water storage of −7.1 cm for non-floating fens and −14.4 cm for floating fens (Fig. 1). Based on soil moisture curves for fibric peat (Boelter, 1988), approximately 50% of the water stored in fens is available and the lowest water table position would be 14.20 cm below the present level in non-floating fens. The mean summer depth of the water

Table 1. *Thirty-year (1955–85) means for climatological variables (June–August) for representative northern stations in Canada*

Station	Location	T_a (°C)	RH (%)	$u_{10\,m}$ (m s^{-1})	P (cm)	Q^* (MJ m^{-2} d^{-1})
Yellowknife, N.W.T.	62° N, 114° W	14.1	64	4.7	8.7	9.11
Churchill, Man.	58° N, 94° W	9.8	78	5.8	14.7	8.65
Kapukasing, Ont.	49° N, 82° W	15.4	71	5.6	27.3	9.54
Nitchequon, Qué.	50° N, 70° W	11.7	74	4.1	29.6	9.65
Goose Bay, Lab.	53° N, 60° W	13.8	66	3.9	27.6	7.29

T_a: air temperature
RH: relative humidity
$u_{10\,m}$: wind speed at 10 m
P: precipitation
Q^*: net radiation

table, predicted by the model, was 5 to 10 cm; the actual mean water table depth in non-floating fens near Schefferville is 8.2 cm (Moore et al., 1990; Roulet, 1991). Thus, the water table could drop to between 19 and 24 cm beneath the peat surface.

In the case of the floating fen, the peat surface rises and falls with changes in the water table, thereby keeping the peat effectively saturated (Roulet, 1991). A survey of 29 randomly-selected fens in the Schefferville area revealed that only 10% were completely free-floating, while the remaining 90% experienced surface changes of between 0.5 and 0.03 cm per cm change in water table position (Roulet, 1991). Hence, in our analysis, we assumed a buoyancy adjustment factor of 0.5, producing a water table drop in the floating fen of 18.7 cm.

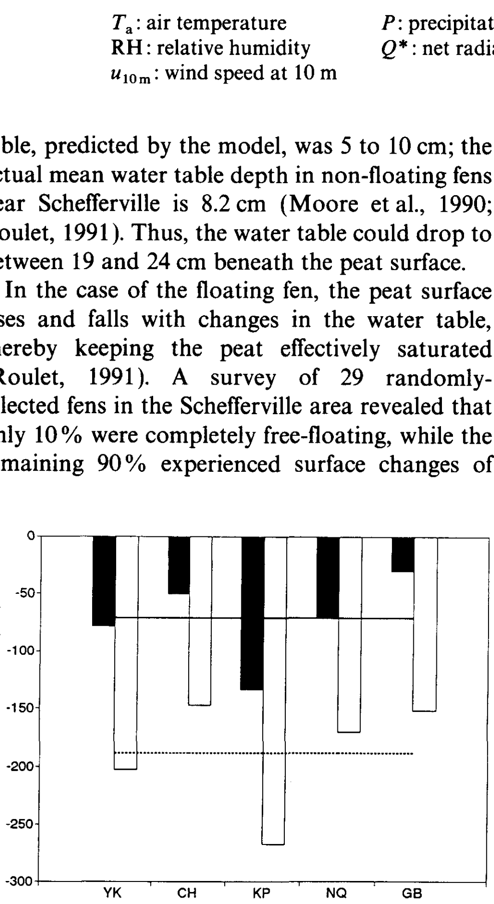

Fig. 1. Predicted change in June, July and August (J, J, A) water deficits between present-day and 2 × CO_2 climate, for fens in five locations in northern Canada. YK = Yellowknife (62° N, 114° W), CH = Churchill (58° N, 94° W), KP = Kapuskasing (49° N, 82° W), NQ = Nitchequon (53° N, 70° W) and GB = Goose Bay (52° N, 60° W). Solid bars indicate non-floating fens and open bars floating fens. Solid and dashed lines indicate the mean deficit for non-floating and floating fens, respectively.

The hydrological model does not contain a feedback between the position of the water table and the resistance to evapotranspiration (i.e., we assume the resistance remains constant). In reality, movement of the water table deeper from the peat surface would probably increase resistance to evapotranspiration. The present model estimates a soil water deficit much greater than that predicted by most climate model experiments which incorporate surface hydrology (e.g., Kellogg and Zhoa, 1988). We believe that this difference arises because wetlands clearly have a greater soil water capacity than the 15 cm "bucket" size commonly assigned to terrestrial ecosystems in climate models. Typical volumetric soil moistures for northern peatlands range between 60 and 80%, so this "bucket capacity" could be contained in the top 20 cm of a peatland.

The peatland to which the relationships were applied is the Capricorn fen located near Schefferville, Quebec (54°48′N, 66°49′W) and described in Moore et al. (1990). This site was chosen because of the availability of data to derive the relationships and has a methane flux in the middle of the range for northern peatlands. It is a small fen of low minerotrophic status (*sensu* Sjörs, 1952), in which the *Carex-Sphagnum*-dominated fen margin passes into a central floating section dominated by *Sphagnum-Carex* and then into a flooded section, in which the water surface overlies the organic mat by about 10 cm. During 1989, the fen showed high methane flux rates, with averages ranging from 65 to 125 mg CH_4 m^{-2} d^{-1} in the margin and central sections to 36 mg CH_4 m^{-2} d^{-1} in the flooded section. Air temperature: peat temperature (Moore and Knowles, 1990, site 1) and water table: methane flux (Fig. 2, Moore et al., 1990) relationships for the margin and central sections of the fen were used in the following analyses.

An increase of 3°C in air temperature produced an increase of approximately 0.8°C at a depth of 10 cm in the peat, using the empirical relationship developed for the Schefferville fen. This may be an underestimate of reality, because the proposed climatic changes will also bring about longer summers, shorter and warmer winters and a thicker insulating snow cover. Thus, for an additional comparison, we have also employed a 2.0°C increase in peat temperature at 10 cm.

The response of methane flux from the fen to changes in peat temperature and position of the water table are indicated in Table 2. The initial or control conditions are the average for the Schefferville fens (Moore et al., 1990). The perturbed conditions were those calculated using the water table and temperature relationships described above. There is a small increase (5 to 13%) in methane flux from a temperature increase of 0.8 or 2.0°C at a peat depth of 10 cm, based on field temperature: flux relationships (Moore and Knowles, 1990). Laboratory and field studies of this relationship for similar peats have found stronger increases in methane production with rising temperature, with Q_{10} values generally ranging between 2 and 3 (e.g., Svensson and Rosswall, 1984; Williams and Crawford, 1984); this would produce predicted increases in methane emission of up to 40%.

A drop in the position of the water table, however, produces a much greater decrease in methane flux (Table 2). The flux is reduced by 74% in a floating fen, with a drop in the water table position from 0 to 14 cm beneath the peat surface. In the non-floating fen, the water table position falls from 8 to 22 cm beneath the peat surface, producing a reduction in methane flux of 81%.

These crude, simplistic calculations suggest that the methane-climate feedback for subarctic fens is very sensitive to small changes in the physical

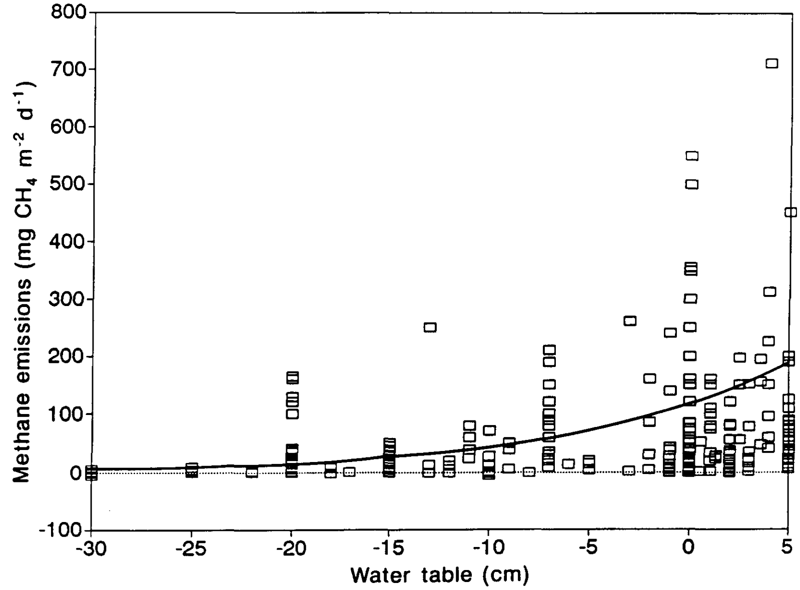

Fig. 2. Methane emission: water table relationship. Data shown as open squares are derived from Bartlett et al. (in press), Crill et al. (1988), Harriss et al. (1982, 1988, 1985), Moore and Knowles (1989, 1990), Moore et al. (1990), Sebacher et al. (1986), Svensson and Rosswall (1984), Whalen and Reeburgh (1988), Wilson et al. (1989). The solid line indicates the best fit ($CH_4 = 116.7e^{0.096wt}$; $r^2 = 0.38$; $S_y = 0.71$) developed from the Schefferville data for the Capricorn fen (Moore et al., 1990). This relationship is similar to that suggested by the literature values.

Table 2. *Estimated change in methane flux from changes in peat temperature at a depth of 10 cm and water table position for the Capricorn fen, Schefferville*

	Variables		Methane flux ($mg\ m^{-2}\ d^{-1}$) [% change over *I*]	
	I	*P*	*I*	*P*
temperature at 10 cm depth (°C)				
	17.5	18.3	75	79 [+5]
	17.5	19.5	75	85 [+13]
water table position (cm beneath peat surface)				
floating fen	0	14	116	30 [−74]
non-floating fen	8	22	74	14 [−81]

I: initial conditions.
P: perturbed conditions.

environment of the peatland. The reduction in methane flux associated with a lowering of the water table results from a decrease in the zone of active methane production under anaerobic conditions and an increase in methane oxidation in the aerobic zone, through which the methane diffuses before being emitted to the atmosphere. Different responses in methane flux are likely to be found in other northern peatlands in which water table: methane flux relationships are different, such as pools or strings in patterned fens (Moore and Knowles, 1990).

Significant rates of methane consumption (2 mg $CH_4\ m^{-2}\ d^{-1}$) have been reported for relatively dry tundra soils as well as temperate forest soils (Steudler et al., 1989; Whalen and Reeburgh, 1990). A combination of a decrease in the source areas for atmospheric methane, coupled with the consumption of methane in drier ecosystems, suggests that the high latitudes would decrease in importance as a net source of atmospheric methane. However, secondary changes in plant composition and production in peatlands will also affect methane flux, though these changes are likely to occur over a longer period of time than those brought about directly by changes in water table and temperature. Reconstruction of palaeo-hydrological conditions of wetlands (e.g., Nicholson and Vitt, 1989) and changes in plant composition and peat accumulation, combined with process studies, will assist in the assessment of longer-term sensitivity of wetlands to climate change and the nature of feedback mechanisms.

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