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TRACE GAS EMISSIONS FROM CANADIAN PEATLANDS AND THE EFFECT OF CLIMATIC CHANGE

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Abstract: The emission of three trace gases, nitrous oxide, carbon dioxide, and methane, from peatlands is examined, identifying the primary controls and the potential effect of climatic change on emission rates. Nitrous oxide emission from natural peatlands is small and tied to the cycling of nitrogen but increases upon disturbance such as drainage. Peatlands generally act as a sink for carbon dioxide, but they convert from a sink to a source upon drainage. Methane emissions are controlled primarily by position of the water table, with secondary controls of temperature and trophic status of the peat. Canadian and other northern peatlands play a moderately important role in the global methane budget. Climatic change, such as increases in temperature and precipitation predicted by 2 × CO_2 scenarios, may result in increased emissions of nitrous oxide, decreased carbon dioxide storage, and reduced methane emissions from Canadian peatlands.

Key Words: carbon dioxide, methane, nitrous oxide, climatic change, peatlands

The concern generated by the increase in atmospheric concentrations of greenhouse gases and resultant predictions of global warming has stimulated an evaluation of the role of peatlands and other wetlands in the global cycle of these trace gases. As well, there is a need to be able to predict the impact of climatic change on the flux of these gases from wetlands under General Circulation Model (GCM) scenarios. Peatlands play a potentially significant role in three trace gases: nitrous oxide [N_2O], carbon dioxide [CO_2], and methane [CH_4]. In this paper, I examine the evidence for the emission of these trace gases from Canadian peatlands, the controls on these emissions, and the potential climatic change effects on these emissions.

NITROUS OXIDE

Emission from soils of nitrous oxide [N_2O] and the other nitrogen oxide gases (nitric oxide [NO] and nitrogen dioxide [NO_2]) results from the cycling of N in the soil. Where N cycling is rapid, through nitrification and denitrification, and the microbial cycle "leaky," significant emissions of these gases are likely to occur (Davidson 1991).

Relatively few data are available on the flux of N_2O from undisturbed peatland soils. In the Hudson Bay lowland, Schiller and Hastie (1994) measured annual fluxes of between −2.1 to 18.5 mg N_2O m^{-2} and estimated emission of N_2O from the whole lowland at 1.2 Gg yr^{-1}. Goodroad and Keeney (1984) observed annual fluxes of 0.02 to 0.08 g N_20 m^{-2} from undrained marshes, Urban et al. (1988) reported fluxes of < 0.2 to 0.6 μg N_2O m^{-2} h^{-1} from Minnesota and western Ontario ombrotrophic peatlands, and Yavitt and Fahey (1993) measured fluxes of 14 μg N_2O m^{-2} h^{-1} from an organic soil in a New England forest. Given the N-poor status of most Canadian and northern peatlands and the slow rate of N cycling, it is not surprising that N_2O emission rates are small. Canadian peatlands probably play a very minor role in the global N_2O emissions from soils (Davidson 1991).

Upon disturbance, however, N_2O fluxes increase because of the faster rate of N cycling in the soil. Goodroad and Keeney (1984) observed annual N_2O fluxes of 0.9 to 2.0 g m^{-2} from drained marshes, and Duxbury et al. (1983) reported annual N_2O fluxes of up to 25 g m^{-2} from drained, cropped, and fertilized sub-tropical peatlands. There may also be significant N_2O emissions from drained and cultivated Canadian peatlands, but data are lacking.

CARBON DIOXIDE

Peatlands generally act as sinks for C, effectively storing atmospheric CO_2. Gorham (1991) estimated that Canadian peatlands contain about 156 × 10^{15} g C, equivalent to about one third of the C stored in global boreal and subarctic peatlands and about 10 %

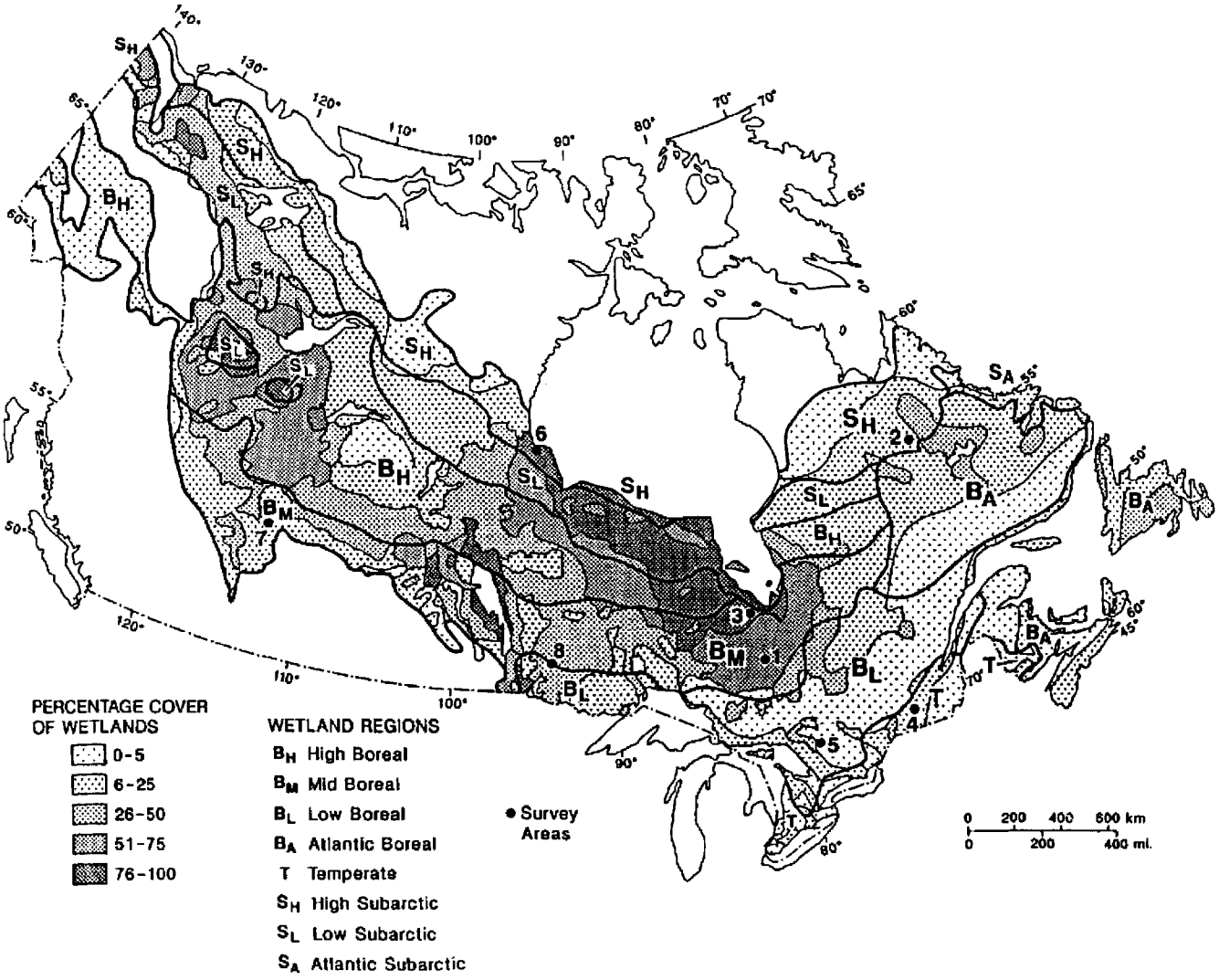

Figure 1. Location of methane flux measurements from peatlands in Canada, with wetland coverage and regions. Locations are: 1—Cochrane, Ont.; 2—Schefferville, Que.; 3—Moosonee, Ont.; 4—Montreal, Que.; 5—Dorset, Ont.; 6—Churchill, Man.; 7—Edmonton, Alb.; 8—Experimental Lakes Area, Kenora, Ont.

of the C stored in all terrestrial soils (Schlesinger 1991). Calculation of long-term C accumulation rates reveals an average of about 30 g m^{-2} yr^{-1} (Gorham 1991), but current accumulation rates may be lower than this figure, based on modelling studies (e.g., Clymo 1993).

CO_2 fluxes in peatlands can be measured at scales ranging from small chambers (< 1 m^2), through micrometeorological towers (several 100 m^2), to aircraft-based platforms (covering several km^2). The CO_2 flux measured is a function of photosynthetic uptake, root respiration, and respiration by soil organisms; partitioning the flux into these components is not easy. Using measurements of CO_2 and CH_4 flux, plant productivity, and root:shoot ratios in a subarctic fen, Moore (1989) estimated that the string (an upraised section of the peatland) was accumulating C at a rate of 38 g m^{-2} yr^{-1} (close to the average historical C accumulation rate of northern peatlands), the flark (a degrading section) was losing C at the rate of 13 g m^{-2} yr^{-1}, and the pool was in approximate equilibrium with respect to C (loss of 2 g m^{-2} yr^{-1}).

Upon drainage, peatlands are converted from a sink to a strong source of CO_2. Based on the area of drained peatlands and observations of the lowering of the peat surface, Armentano and Menges (1986) estimated that temperate peatlands, as a whole, may have changed from an overall sink to a source of C. In peatlands near Montreal drained for horticultural crop production, spring- to-autumn CO_2 flux ranged from 0.6 to 1.0 kg C m^{-2} (Glenn et al. 1993), suggesting that much of the observed rates of surface lowering of the peat (generally 2 to 5 cm yr^{-1}) is probably through subsidence and aeolian erosion, rather than direct oxidation of the peat profile.

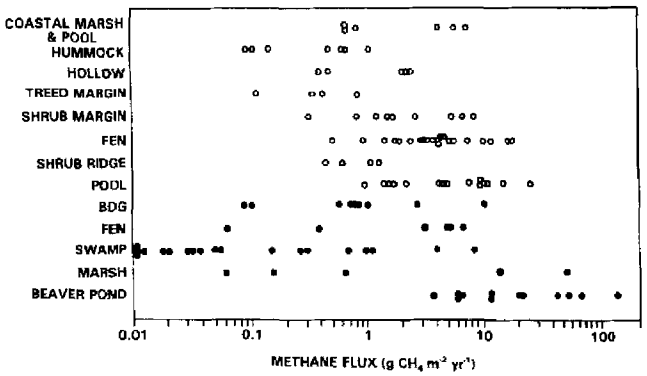

Figure 2. Annual methane emissions from Canadian peatlands, grouped by broad ecological class for subarctic (open circles) and boreal-temperate (shaded circles) regions. Estimates were derived from Moore and Knowles (1990), Moore et al. (1990, 1994), Holland (1992), Roulet et al. (1992a), Bubier et al. (1993a), and Windsor (1993).

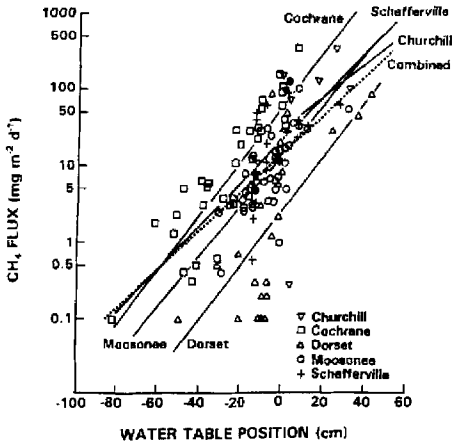

Figure 3. Relationship between seasonal mean methane flux and seasonal mean water table position for peatlands in several Canadian regions (from Moore and Roulet 1993).

METHANE

Of the trace gases, most progress has been made in the measurement of CH_4 flux from Canadian wetlands, the controls on the flux, and the role of Canadian peatlands in the global CH_4 cycle. The flux of CH_4 from a peatland is a function between the rates of CH_4 production and consumption in the profile and the transport mechanisms to the atmosphere, such as diffusion, ebullition, or plant-mediated movement. As with CO_2, flux measurements can be made at scales ranging from < 1 m^2 (chambers) to several hundred m^2 and km^2 (micro-meteorological towers and aircraft platforms).

Measurements of CH_4 flux (generally from static chambers) are now available for a number of sites across Canada, representing many of the most important peatland regions (Figure 1). Fluxes (generally over the snow-free season but assumed to represent most of the annual flux) range from 0 to over 50 g m^{-2} y^{-1}, with a few sites showing small CH_4 consumption rates of < 1 g CH_4 m^{-2} y^{-1} (Figure 2). There are wide variations in flux from sites in the same broad ecological peatland class. Measurements with chambers are plagued by high values of spatial variability (with within-site coefficients of variation of 50 to 100% being common), so that flux estimates are often imprecise, and a large number of chambers (15 to 20) need to be employed at each site if reasonably precise estimates are to be obtained. Temporal variability in CH_4 flux can also be large; Windsor et al. (1992) observed episodic fluxes of CH_4 from subarctic fens, related to thawing of ice and summer falls in water table position, which would be missed by infrequent sampling schemes, resulting in an under-estimate of the overall flux by up to 20 %.

Three main factors can be identified in the control of CH_4 emissions from peatlands: temperature (as a control on microbial activity), water table position (as a surrogate for aerobic/anaerobic conditions), and peat/tissue type (as the substrate for microbial methanogenesis and methanotrophy). In addition, there is evidence from northern peatlands that some vascular plants, such as sedges, can enhance CH_4 emission rates (e.g., Bartlett et al. 1992, Whiting and Chanton 1992).

Attempts to relate temporal patterns of CH_4 emission to thermal and hydrologic regime have met with variable success. The development of strong relationships has been obtained in Minnesota peatlands (e.g., Crill et al. 1988, Dise et al. 1993), but in other areas the relationships have been weak (e.g., Moore and Knowles 1990, Moore et al. 1991, Roulet et al. 1992). In part, this is because of the difference in temperature dependence of methane production and consumption (Q_{10} values of 2.1 to 6.8 and 1.2 to 2.1, respectively; Dunfield et al. 1993) and increased emission of CH_4 during the fall of the water table, with a resulting hysteresis effect on the falling and rising limbs (Moore and Dalva 1993).

When comparisons are made of mean seasonal CH_4 emission rates among sites within a wetland region, water-table position exerts a strong control, with regression coefficients (slopes) that are remarkably similar, although the regression constant varies among regions (Figure 3; Moore and Roulet 1993). Differences in CH_4 flux from microtopographic features such as hummocks, hollows, and lawns can similarly be explained by differences in water-table position and the capacity of the peat profile to produce and consume CH_4 (Bubier et al. 1993b). Temperature differences seem to be of secondary importance, although there is often a strong association between peat temperature and water-table position. As plant distribution is affected by temperature, water-table position, and tro-

Table 1. CH_4 emissions from beaver ponds and margins.

Source	Location	Ecological Site	Annual Flux (g CH_4 m^{-2} yr^{-1})
Bubier et al. (1993a)	northern Ontario	Marsh (−18 cm water)	0.7[2]
		Marsh (−3 cm water)	13.4[2]
		Submerged (5 cm water)	52.5[2]
		Deep water (50–150 cm water)	43.7[2]
Ford and Naiman (1988)	Sept-Iles, Québec	Undisturbed stream	0.1–0.4
		Beaver pond	5.9
Naiman et al. (1991)	northern Minnesota	Upland Forest	0.3
		Sedge Meadow	0.5
		Submergent (45 cm water)	14.3
		Deep Pond (125 cm water)	11.6
Roulet et al. (1992)	southern Ontario	Beaver pond	7.6
Vitt et al. (1990)	central Alberta	Beaver pond	76.2
Weyhenmeyer (1992)	southern Ontario	Beaver pond	6.2
Windsor (1993)	southern Québec	Submerged margin (5–10 cm water)	78
		Shallow water (15–50 cm)	130
Yavitt et al. (1990)	W. Virginia, Maryland	Beaver pond	300, 250[1]
Yavitt et al. (1992)	New York	Beaver ponds	34–40

[1] daily flux (mg CH_4 m^{-2} d^{-1}) reported at two dates, expressed as mean and median;
[2] assuming a season of 150 d, for which the rates from early-June to mid-August were representative, and no significant emission of methane during the winter.

phic status, plant species may be a good predictor of CH_4 flux. Bryophytes seem to be more sensitive than vascular plants to water-table position, and we have been able to predict CH_4 flux from peatlands based on the occurrence of *Sphagnum* and other bryophyte species (Bubier et al. in press).

Laboratory incubations of peat samples under aerobic and anaerobic laboratory conditions indicate the wide range in potential rates of CH_4 consumption and production within and among peatlands. In the Hudson Bay Lowland, for example, potential production and consumption rates range over 3 orders of magnitude and help explain differences in field CH_4 fluxes beyond that which can be gained by water-table position and temperature (Moore et al. 1994). Controls on microbial methanogenesis and methanotrophy are complex. Dunfield et al. (1993) have shown that pH exerts an effect, with an optimum pH for CH_4 production and consumption between 5.0 and 7.0, about 2.0 units higher than soil pH in acidic peats and < 1 pH unit higher in less acidic peats. The mechanisms are complicated and may involve controls of the production or loss of precursors to the CH_4 transformations. Although there is a pH-dependence of CH_4 production and consumption in laboratory incubations, peat pH, or overall trophic status, seems to exert little control on field CH_4 flux because the controls exerted by water-table position and temperature are more important.

Beaver ponds emit between 5 and 50 g CH_4 m^{-2} yr^{-1} to the atmosphere (Table 1), but the reasons for this variability are not well understood. It may be a function not only of water depth but also of age and activity of the pond. CH_4 flux is also large on the pond margins, where the soil is just above or just below the water table, and this zone is liable to strong spatial fluctuations with beaver cycles (Naiman et al. 1991).

Although the estimates of CH_4 emission rates from peatlands are laden with errors and uncertainties, estimates of the contribution to the global CH_4 budget can be made. Taking an average annual emission from Canadian peatlands of 2 g CH_4 m^{-2} and a coverage of 1.3×10^{12} m^{-2}, Canadian peatlands emit an estimated total of 2 to 3 $\times$ 10^{12} g CH_4 yr^{-1}. However, there are regions in which CH_4 emissions may be larger, such as the southern boundary of the boreal forest in Minnesota (e.g., Crill et al. 1988), but the extent of these areas is unclear. The estimate of 20 to 30 $\times$ 10^{12} g CH_4 yr^{-1} for the contribution of Canadian and other northern peatlands (40 to 70° N) to atmospheric CH_4 is smaller than had originally been thought but is similar to recent estimates based on global models (e.g., Fung et al. 1991).

THE IMPACT OF CLIMATIC CHANGE

Although there are some disagreements, all the GCM scenarios based on doubled atmospheric CO_2 concentrations predict substantial increases in temperature (particularly during the winter) in the areas of major Canadian wetland coverage (e.g., Mitchell 1989). Changes in precipitation are less substantial but suggest a slight increase. How are these changes in climate likely to affect emission of trace gases from peatlands?

The paucity of data on N_2O and CO_2 fluxes from peatlands makes prediction difficult. Increased cycling of N, related to warmer temperatures or changes in plant cover, may stimulate increased N_2O emission from undisturbed peatlands. However, drainage, cultivation, harvesting, fertilizing, and other anthropogenic changes in peatlands are likely to be a much more important cause of significant increases in N_2O emission.

Changes in C storage in peatlands will be dependent on the balance between rates of plant production and tissue and peat decomposition. Warmer temperatures and a lowered water table are likely to result in enhanced CO_2 emissions and reduced C storage (Gorham 1991, Hogg et al. 1992, Moore and Dalva 1993).

As more is known about the controls on CH_4 emission from peatlands, the approaches available to answer the climatic change question can be illustrated with respect to CH_4. The three controls of temperature, water-table position, and plant production and tissue quality are likely to change in response to changing climate, and the resulting change in CH_4 flux will be the balance between the competing influences of these three factors.

The question can be answered in three main ways.
1) The measurement of CH_4 fluxes over a number of years at the same site can be used with a climate analogue approach to estimate fluxes under the GCM scenario conditions. Research projects are rarely designed to measure fluxes over many years, but there are studies that show that substantial year-to-year differences in CH_4 flux can occur, for example, Moore and Knowles (1990) in temperate swamps and subarctic fens, Whalen and Reeburgh (1990) in tundra, and Holland (1992) in subarctic fens.
2) The relationships established between the environmental variables and CH_4 emission rates can be combined into models in which the variables can be modified in accordance with predicted changes associated with GCM scenarios. An example of this approach is the study of a subarctic fen by Roulet et al. (1992). Based on GCM predictions of changes in air temperature and precipitation, predictions were made of the increase in surface peat temperature and decrease in the position of the water table (derived from changes in precipitation and evapotranspiration and the storage capacity of the peat). These changes were then applied to empirical relationships of CH_4 flux, temperature and water-table position developed from field measurements, and the resulting changes in flux calculated. These calculations suggested that although increased peat temperature would be expected to increase CH_4 flux, the more dominant influence was exerted by the fall in the water-table position, resulting in an overall decrease in flux of between 74 and 81%, compared to present-day conditions. A similar approach could be applied to other peatland types.
3) Measurements of flux can be made at sites that have been perturbed in ways similiar to that expected by climatic change. For example, Roulet et al. (1993) measured CH_4 flux at sites along transects perpendicular to drainage ditches installed in the Wally Creek Experimental Forest catchment near Cochrane, northern Ontario. Water tables were lowered from depths of 10 to 20 cm at the undisturbed sites to up to 80 cm near the ditch, and the peat was cooler. The result was that the peatland was converted from a CH_4 source (0 to 8 mg CH_4 m^{-2} d^{-1}) to a sink (uptake of 0.1 to 0.4 mg CH_4 m^{-2} d^{-1}).

However, none of the above approaches adequately takes into account the changes in vegetation that are likely to result from climatic change and their effect on CH_4 emissions, both directly as a transport mechanism and indirectly through the influence of plants on nutrient cycling and substrate quality.

CONCLUSIONS

Although measurements of N_2O flux from peatlands are few, the flux is likely to be insignificant, except where there is a rapid rate of N cycling, input of N-rich water or drainage, and fertilization. Changes to the global N_2O cycle are more likley to result from these anthropogenic changes rather than broad climatic change.

Peatlands act as both a significant store of C and a sink for CO_2. The storage is likely to decrease with drainage or climatic change resulting in warming and water-table lowering, with many peatlands becoming a source of CO_2.

Canadian and other northern peatlands and wetlands are significant sources of atmospheric CH_4 at the global scale. Although the primary controls on CH_4 emission rates have been established, further work is needed to develop models that incorporate rates of CH_4 production and consumption in the peat profile with transport by diffusion and ebullition and the role of plants. Longer-term measurements of CH_4 flux at selected sites are needed. The small-scale variation in CH_4 emission rates means that spatial estimates of flux may be imprecise, with problems in attempting to scale up to regional and global flux estimates. Vegetation, especially bryophytes, and water-table depth offer ways in which simple field measurements could be used to estimate CH_4 flux.

CH_4 flux is affected by direct anthropogenic activities, such as drainage, as well as indirect activities, such as the control of beaver populations and their ponds. Modelling of CH_4 based on water table and temperature suggests that northern peatlands may have smaller

CH_4 emissions under GCM climate change scenarios. The development of longer-term measurements of flux will aid in assessing the impact of climatic change.

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