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METHANE FLUX FROM BOREAL PEATLANDS

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The peatlands found in the boreal zone (roughly 45°–60°N) store a significant reservoir of carbon, much of which is potentially available for exchange with the atmosphere. The anaerobic conditions that cause these soils to accumulate carbon also makes wet, boreal peatlands significant sources of methane (CH_4) to the global troposphere. We estimate that boreal wetlands contribute approximately 19.5 Tg CH_4 yr^{-1}. The data available on the magnitude of boreal CH_4 emissions have rapidly accumulated in the past twenty years. This paper offers a short review of the flux measurements (which range from roughly 1 to 2 000 mg CH_4 $m^{-2}d^{-1}$), considers environmental controls of the flux and briefly discusses how climate change might affect future fluxes.

Keywords: Carbon, climate change, global change

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INTRODUCTION

The peatlands of the boreal zone represent an enormous reservoir of carbon with ca. 192–455 Pg C (= 10^{15} g) stored in its soils and peats alone (Post et al. 1982, Gorham 1991). This represents between 14 and 33% of the total world pool of soil carbon estimated by Post et al. (1982) and is an amount equal to about 60% of the current atmospheric burden of CO_2–C. Most of this peatland carbon is potentially available for exchange with the atmosphere (Billings 1991). It is the exchange between reservoirs rather than simply the storage term that is of interest. For example, Schlesinger (1984) points out that a 1% increase in oxidation of all soil organic matter would increase the supply of CO_2 to the atmosphere of on the order of 1 Pg yr^{-1}.

The role of northern latitude sources in mediating the global carbon cycle has become a very important issue because of recent developments of general circulation models and observed patterns of CO_2 distributions in the global atmosphere and oceans point to the possibility of a significant CO_2 sink of 2–3 Pg yr^{-1} in the boreal zone of terrestrial landmasses (Tans et al. 1989, 1990). Other models (e.g. Bonan 1991a, b) also indicate the taiga to be a significant carbon sink but of about half the magnitude estimated by Tans et al. (1989). In any event, the range (0.9–3 Pg yr^{-1}) of the sink is on the same order as the current increase in atmospheric CO_2 observed at Mauna Loa (Keeling et al. 1976) and from the GMCC/CMDL network (Conway et al. 1988).

Natural wetlands are significant sources of atmospheric methane (CH_4). Models of $^{14}CH_4$ (Wahlen et al. 1989) and of wetland distribution and flux (Matthews & Fung 1987, Aselmann & Crutzen 1989) as well as earlier estimates (e.g. Ehhalt 1974) indicate that wetlands contribute from 19–27% of the estimated total CH_4 emissions which is equivalent to an annual range of flux of between 30 to 300 Tg (Tg = 10^{12} g). Within the past five years, as more data have accumulated, there has been a growing consensus among the various estimates toward an annual global flux of about 110 Tg CH_4 (Matthews & Fung 1987, Bartlett et al. 1990, Fung et al. 1991). Boreal mid-continental peatlands and wet tundra are significant sources of atmospheric CH_4 (e.g. Harriss et al. 1985, Moore & Knowles 1987, Crill et al. 1988, Moore et al. 1990, Bartlett et al. 1992, Roulet et al. 1992a, b) and, if peats are accumulating in high latitude environments, a net sink for CO_2.

Besides the strictly budgetary concerns of CH_4 sources, northern wetlands are potentially unique environments for the study of biosphere–atmosphere–climate interactions. Any global warming or cooling will probably be enhanced in northern latitudes (e.g. Hansen et al. 1988) with direct effects on emissions of CH_4 and therefore direct consequences on global CH_4 and climate cycles. An understanding of the mechanisms that control and regulate CH_4 (as well as other trace gases) fluxes from northern wetlands is particularly important.

A BRIEF HISTORY OF THE REGIONAL FLUX ESTIMATE

Clymo and Reddaway (1971) were the first to report measurements of CH_4 emissions from wetlands in the high latitudes as part of their pioneering carbon budget work at Moor House Reserve in Great Britain. Matthews and Fung in 1987, based largely on northern emissions reported by Sebacher et al. (1986), estimated that northern wetlands (50°–70°N) supplied an annual flux of 62 Tg or roughly 60% of the total contribution from all wetlands to atmospheric CH_4. Since then the number of flux measurements from high latitudes has increased rapidly. Utilizing the improved flux data base, Bartlett et al. (1990) made a recent recalculation of the global contribution from wetland ecosystems based on the Matthews and Fung wetlands areas and model that suggests that global emissions from northern high latitude areas may be significantly lower than that estimated by Matthews and Fung at 39 Tg yr^{-1}, but are still substantial. Aselmann and Crutzen (1989) also calculated northern emissions to be somewhat lower at about 24 Tg yr^{-1}. The most recent emissions estimates from arctic areas above 60°N are approximately 10–11 Tg yr^{-1} (Bartlett et al. 1992, Fan et al. 1992). These estimates suggest that most of global high latitude CH_4 comes from the boreal zone of roughly 45°–60°N. However, it is to be expected, as the degree of spatial and temporal complexity expressed in the measurements becomes more apparent as the data base improves, that our ability to make large scale generalizations about emissions will become more difficult.

Table 1 (a portion of a table compiled by one of the authors, K.B., for a recent report to the U.S. Environmental Protection Agency) lists reported flux measurements from boreal wetlands, covering a latitudinal range of 45° to 60°N. Measurements range over three orders of magnitude, from less than 1 to roughly 1 940 mg CH_4 m^{-2} d^{-1} and include a wide variety of vegetation, moisture and soil types. A single flux roughly an order of magnitude greater than all others at this site of 12 068 mg CH_4 $m^{-2}d^{-1}$ is reported from an Alberta beaver pond. Since the degree of soil wetness strongly influences anoxia, a necessary condition for methanogenesis, soil moisture is a major factor controlling CH_4 production and release (e.g. Svensson & Rosswall 1984, Sebacher et al. 1986). Wet soils, however, vary greatly in emissions. Moist to dry wetland soils (i.e. no standing water at the soil surface) can be either small sources or sinks to the atmosphere. For example in the arctic, relatively dry soils frequently appear to be small sources, on the order of 0.6–11 mg CH_4 $m^{-2}d^{-1}$ with sporadically occurring consumption of atmospheric methane of between –0.5 and –3 mg CH_4 m^{-2} d^{-1} (King et al. 1989, Whalen & Reeburgh 1990a, b, Bartlett et al. 1992, Fan et al. 1992). In the northern temperate to boreal zone, drier wetland soils are usually invaded by shrubs and trees, where a consistent pattern of CH_4 consumption on the order of –0.05 to –4 mg CH_4 $m^{-2}d^{-1}$ appears to exist (Crill 1991, Born et al. 1990).

BOREAL METHANE EMISSIONS

Most of the fluxes measured in the boreal zone (roughly 45°–60°N) are primarily from two areas — in and around the Marcell Experimental Forest and the Red Lake Peatland of northern Minnesota and in the Schefferville area and the Hudson Bay Lowlands of Canada. Emissions from more western sites in Canada (Alberta) have also been recently examined (Vitt et al. 1990). Significant differences appear to exist between the two major regions. Measurements reported from Minnesota are generally significantly higher than those from Canada, even though the ranges overlap and much of the vegetation and general topography are similar. For example, comparing emissions from these areas from wet bogs and fens (Table 1), flux from Marcell and vicinity averages 237 ± 48 mg CH_4 $m^{-2}d^{-1}$ (standard error of the mean (S.E.), n = 13; ranging from 93–402 mg CH_4 $m^{-2}d^{-1}$) compared to the flux from the Schefferville area which averages 33 ± 6 mg CH_4 m^{-2} d^{-1} (n = 14; 0.7–72 mg CH_4 $m^{-2}d^{-1}$). The emissions from wet bogs and fens from all sites in Canada averages 29 ± 6 mg CH_4 $m^{-2}d^{-1}$ (n = 40; 0–148 mg CH_4 $m^{-2}d^{-1}$). The Red Lake Peatland closely resembles the Hudson Bay Lowlands region but has somewhat less open water (Glaser et al. 1981). However, comparison of the Hudson Bay data with those collected from Red Lake reported in Crill et al. (1988), finds that the striking regional differences are maintained. Vitt (pers. comm. to K.B.) suggests that a regional shift in predominant mineral status, even within a habitat type (e.g. mineral poor vs. mineral rich fens) can result in significantly different large scale flux estimates. These regional differences make it difficult to extrapolate flux measurements to other regions even though vegetation and climate regimes may be broadly similar.

Even though the current data base is limited, areas flooded by beaver populations may be a significant source of atmospheric CH_4 (Table 1, refs. 5 and 9). The open water area of ponds sampled by Roulet et al. (1992a) suggest that release rates may be highly variable, averaging from 30 to 91 mg CH_4 $m^{-2}d^{-1}$. Emissions from these sites are likely to be dependent upon such variables as time since flooding, plant species present, dam integrity, water depths and even air pressure (Mattson & Likens 1990). The measurements to date suggest that fluxes are not greatly different from "natural" small ponds and surrounding wetlands but that beaver-impacted areas may have shorter lifetimes as atmospheric CH_4 sources since they are dependent upon dam integrity for inundation. The regional importance of beaver ponds is likely to be highly variable since beaver populations commonly exhibit large spatial and temporal changes.

The comparison of flux measurements within one boreal region that were made at different times and by a variety of investigators suggests, that although there may be significant spatial and temporal variability, average measurements are in general agreement. This is true, in part, because of the relatively high variance of the flux measurements (e.g. in Marcell Forest, S.E. range from 3% to 35% of means, Harriss et al. 1985, Crill et al. 1988, Dise 1992). Dise (1991, 1992) reports the only annual multi-year flux data set from the boreal zone from sites that were originally studied by Harriss et al. (1985) in 1983 and by Crill et al. (1988) in 1986. Although there were significant differences in the magnitude and timing of emissions from year to year, there were few significant differences between the data reported by the various investigators. Monthly emissions could vary by as much as two- to three-fold at sites, while annual emissions generally varied roughly 10–30% between years (Dise 1992). Moore and Knowles (1990) report multi-year summer fluxes from a variety of Canadian sites. Average CH_4 emissions from all sites varied from nearly two- to somewhat more than three-fold between years, similar to year-to-year differences from the Minnesota sites.

NOWES/ABLE 3B was an integrated Canadian/U.S. flux measurement campaign involving chamber enclosure measurements and eddy correlation flux measurements made from micrometeorological towers and from several aircraft was conducted in the Schefferville and the Kinosheo Lakes areas of Canada in 1990. For a total of seven tower to enclosure comparisons, fluxes were within a factor of 1.2 on 4 dates and within a factor of 2 on 3 days (Roulet, unpublished data). Aircraft and tower eddy correlation fluxes were in good agreement (Table 1, refs. 11–13). Data also agreed with earlier measurements made in this area (Moore & Knowles 1987, Moore et al. 1990).

METHANE FLUX AND ENVIRONMENTAL CONTROLS

Most work on methane emissions from the high latitudes finds qualitative rather than quantitative links between flux and such obvious environmental factors as water table level and soil temperature. This is largely due to the variety of environmental factors that affect the release of methane from soils. Dise (1991) used a multiple regression statistical approach to determine quantitative relationships between water level, seasonal soil temperature and flux for a series of bogs and fens in northern Minnesota. Water table was found to explain 62% of the variability in flux. The addition of annual soil temperature change to the regression equation resulted in accounting for 90% of the annual variability. An additional variable that explained some of the residual uncertainty in this model was the von

Table 1. Methane flux measurements from boreal wetlands. Fluxes made using enclosure techniques unless otherwise noted. Flux units are in mg CH_4 $m^{-2}d^{-1}$.

Habitat	Lat.	Average flux	Annual flux ($g/m^2/yr$)	n	Range	Site	Meas. period	Reference
Forested bogs	47°	100	–	8	19–206	Minnesota, Marcell Forest & Zerkel	Aug.	Harriss et al. 1985 1
Nonforested bogs	47°	306	–	24	33–1943			
Forested fens	47°	85	–	5	3–171			
Wild rice bed	47°	493	–	4	127–883			
Sedge meadow	47°	664	–	1	–			
Forested bogs	47°	89	–	55	11–694	Minnesota, Marcell Forest & Red Lake	May–Aug.	Crill et al. 1988 2
Nonforested bogs	47°	199	–	77	18–866			
Forested fen	47°	142	–	12	68–263			
Nonforested fens	47°	348	–	35	152–711			
Nonforested bog	47°	177	–	eddy corr.	120–270	Minnesota, Marcell Forest	Aug.	Verma et al. 1992 3
Forested bog (hummock)	47°	21	3.5	36	2–48	Minnesota, Marcell Forest	Annual	Dise 1992 4
Forested bog (hollow)	47°	93	13.8	36	6–246			
Fen lagg	47°	1211	2.6	27	–1–482			
Nonforested bog	47°	356	43.1	68	0–1056			
Nonforested fen	47°	402	65.7	37	11–767			
Nonforested bog	54–55°	0	0	90	0	Alberta, Canada	May–Oct.	Vitt et al. 1990 5
Nonforested poor fen	54–55°	1	0.1	90	0–22			
Nonforested rich fen	54–55°	65	9.5	90	0–1976			
Forested rich fen	54–55°	24	3.4	90	0–1820			
Sedge meadow	54–55°	148	21.7	90	0–1985			
Beaver pond	54–55°	518	76.2	90	0–12068			
Nonforested fens	55°	30.5	–	80	0–112	Schefferville, Canada	June–Aug.	Moore & Knowles 1987 6
Nonforested fens:								
center	55°	72	–	205	29–125	Schefferville, Canada	June–Sept.	Moore, Roulet & Knowles 1990 7
margin	55°	30	–	195	9–65			
pools/flooded	55°	33	–	–185	24–40			
Forest/fen margin	55°	28	–	255	0.6–51			
Patterned nonforested fens:								
ridges	55°	7.5	–	110	5–9			
pools	55°	48	–	85	32–66			
(calc. regional mean)$^+$	55°	18						
Horiz. rich fen	55°	–	3	–	–3–176	Schefferville, Canada	May–Sept. (multi-yr)	Moore & Knowles 1990 8
Horiz. poor fen	55°	–	9.8	–	12–343			
Ribbed fen:								
ridge	55°	–	1.3	–	1–25			
pools	55°	–	4.5/9.9	–	1–260			
Basin swamps	45°	–	1.2/4.2	–	–3–207	Mont St. Hilaire, Canada	May–Aug. (multi-yr)	
Domed bog:								
center	45°	–	0.1	–	–11–10			
margin	45°	–	0.1	–	–10–9			

(Contnd.)

Table 1. Contnd.

Habitat	Lat.	Average flux	Annual flux (g/m^2/yr)	n	Range	Site	Meas. period	Reference
Beaver ponds	45°	90.6	7.6	56	0.9–246	low boreal forest, Canada	May–Oct.	Roulet et al. 1992a 9
	45°	29.7	7.6	65	0.3–300			
	45°	47.4	7.6	65	0.2–369			
Conifer swamps	45°	7.1	0.18	123	–0.2–236			
	45°	0.15	0.18	132	0.1–10			
	45°	0.2	0.18	148	–0.2–6			
	45°	0.2	0.18	149	–0.2–9			
Mixed hardwood swamps	45°	1.2	0.1	141	–0.3–28			
	45°	0.25	0.1	139	–5.8–10			
Thicket swamps	45°	69.3	4.7	145	0–304			
	45°	0.4	4.7	144	–0.3–37			
Marshes	45°	1.2	0.1	72	–0.1–36			
	45°	0.5	0.1	134	–0.3–26			
Open bog	45°	20.6	1.7	65	–0.1–140			
Forested bog	45°	5.8	1.7	68	–0.1–107			
Fen	45°	3.0	0.4	62	–0.2–78.2			
Blanket bog:								
pool	55°	–	9.3	36	–	Moor House Nat. Res., England	Annual	Clymo & Reddaway 1971 10
lawn	55°	–	5.3	36	–			
hummock	55°	–	1.3	36	–			
(integrated areal means)	55°	–	–	–	0–50	Hudson Bay Lowlands, Canada	July	Schiff et al. 1991, Ritter et al. 1991 11, 12
(integrated areal mean)	55°	16	–	–	–	Kinosheo Lake, Canada	July	Edwards et al. 1991 13
Ponds and lakes	55°	26	–	–	–	Kinosheo Lake, Canada	July	Hamilton et al. 1991 14
Fen ponds	56°	160	–	–	–	Coastal & int. Hudson Bay		
Open water	55°	12	1.5	–	0.2–146	Southern Hudson Bay, Lowlands, Canada	June–Oct.	Roulet unpublished data 15
Marshes	55°	31	2.3	–	–2.3–274			
Shrub and treed fen	55°	2.5	0.4	–	–2.4–32			
Open fen	55°	7.9	0.7	–	–1.6–298			
Fen pools	55°	133	13.8	–	21–544			
Bog pools	55°	60	6.1	–	2.2–665			
Open bog	55°	54	4.6	–	–1.7–1356			
Shrub-rich bog	55°	48	4.0	–	–1.5–1627			
Treed bog	55°	1.8	0.2	–	–1.7–66			
Conifer forest	55°	3.3	0.2	–	–2.2–50			

[+] Calculated based on habitat-specific fluxes and regional habitat coverage data.

Post peat humification index, a measure of the degree of decomposition. When specific sites were examined separately, soil temperature rather than water level explained most of the variability. Moore et al. (1990) found that although flux was only poorly correlated with water table and temperature at any one of their sites, examination of the entire data set indicated a relationship between both variables and flux.

Besides Svensson (1976), who reported a quantitative relationship between flux and soil moisture (as % dry weight), statistically significant correlations with flux are generally limited to soil temperature. Fig. 1 illustrates data from Minnesota, Sweden and Alaska for which a significant correlation between flux and temperature was found. Soil temperatures are from 2–3 cm for the Swedish data, 10 cm for the Minnesota data, and 15 cm for the Alaskan data. All of the data clearly fall along a similar line, although considerable variability within each of the data sets may be present. It is interesting to note the Alaska data on Fig. 1. The soil temperatures from Alaska are from a slightly greater depth and are thus somewhat less variable. Also the Alaskan data cover a much smaller range in both temperature and flux than the other two data sets. Data from the drier Alaskan upland tundra is offset from the other, wetter environments but still appears to parallel the trend of logarithmically increasing flux with increasing temperature. These data demonstrate the striking similarity in slopes for these relationships. These similarities hold both for habitats within a single region (in Minnesota, for fen, open bog and forested fen; for the Yukon–Kuskokwim Delta, for upland and wet meadow tundra) and across arctic and boreal zones. Although this similarity may be a function of the limited data base to date, it may instead imply a more fundamental relationship between temperature and methane release across a variety of high latitude environments. If such is the case, and additional data are found to fall within the range illustrated in Fig. 1, it may be possible to model flux to temperature on relatively large scales. It should be noted however, that these

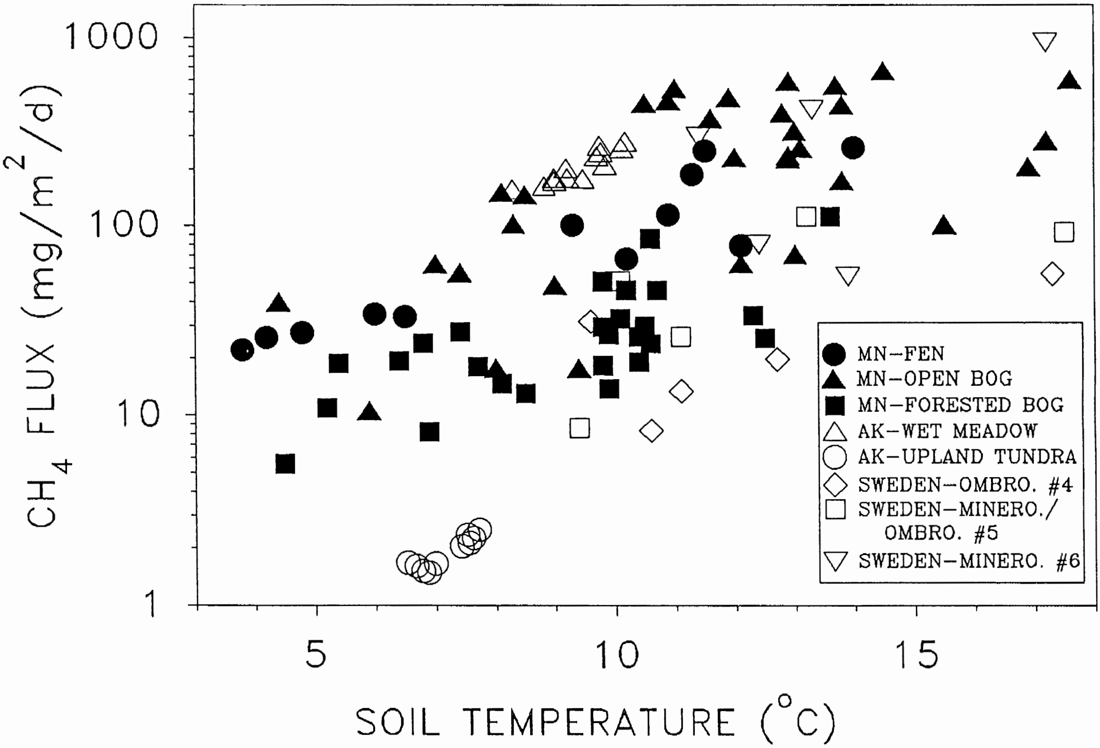

Fig. 1. Methane flux and soil temperatures from northern wetlands. Soil temperatures from Minnesota are measured from 10 cm; those from Alaska at 15 cm (an average of those between 10 and 20 cm); and those from Sweden at 2 cm (from Harriss et al. 1992).

flux:temperature data are seasonal data sets within which additional variables are changing. Manipulative temperature experiments in the field or in mesocosms such as phytotrons may serve to clarify the effects of interdependent environmental variables.

ESTIMATING GLOBAL CONTRIBUTIONS FROM BOREAL WETLANDS

Using an average flux for wet soils only of 87 mg CH_4 $m^{-2}d^{-1}$ from Table 1 and the emission season assumptions and wetland area figures for forested and nonforested bogs from Matthews and Fung (1987), a rough estimate of the magnitude of global emissions from these regions can be calculated. Wetland area for the boreal zone (45°–60°N) is 1 495 x 10^{12} m^2. Boreal wetlands are predominantly forested and nonforested bogs and fens but there are also relatively small areas of swamps (0.15 x 10^{12} m^2). The assumed emission period (assuming winter fluxes to be zero) is 150 days for 45°–60°. Given this model, annual emissions from areas of wet soils in the boreal region are 19.5 Tg yr^{-1}. Wet peatlands in the boreal zone could be supplying about 18% of the total annual wetland flux of CH_4 to the atmosphere. This calculation could be an underestimate if winter season emissions from the boreal zone are significantly larger. Areas of wetlands calculated by Matthews and Fung (1987) are for inundated soils only, so calculation of emissions from moist to dry soils in the boreal regions is difficult. Estimation of the contributions made to atmospheric CH_4 from lakes and ponds is also difficult since there are no global estimates of their areas. Small lakes and ponds are typical of the boreal zone and may well be included in estimates of areas of wet soils.

Regional mean fluxes, derived from either extrapolating enclosure measurements using habitat coverage data or from larger scale measurement techniques such as eddy correlation, offer another way to make regional cross-comparisons. Regional average fluxes incorporate both differences in habitat-specific emissions and differences in ratios of wet and dry habitats within an area. Regional estimates from the Canadian Schefferville/Hudson Bay Lowlands area are uniformly lower than those from northern Minnesota although both regions have abundant areas of wetlands and many small lakes. The Schefferville estimates generally appear to be closer to the flux estimates from the North Slope of Alaska which range from 0.3 to 266 mg CH_4 $m^{-2}d^{-1}$ (Sebacher et al. 1986, Morrissey & Livingston 1992). These differences reemphasize the variability in areas that emit methane and the difficulty in extrapolating even relatively large scale measurement techniques to global scales.

Large scale emissions estimates for the high latitudes necessarily have considerable confidence intervals associated with them. In addition to the problems in spatial variability and extrapolation discussed above, are uncertainties in temporal variability such as the importance of winter emissions and relationships to seasonal temperature change. Much of this uncertainty, however, can be reduced with additional data from both a broader variety of sampling sites and from year-round, multi-year data sets. It is clear that additional survey measurements of flux are needed in areas such as the vast Siberian lowlands since regional comparisons have shown that extrapolations from one region to another are unreliable. The volume of data accumulated in only the last few years suggests that progress in decreasing uncertainties can be rapid.

CLIMATE CHANGE AND WETLAND EMISSIONS

Methane flux to the atmosphere from wetlands can be thought of as a simple equation consisting of three more complex variables:

$$\text{Flux} = \text{Emission rate} \times \text{Wetland area} \times \text{Emission period}$$

Imbedded in the "emission rate" term are the significant diurnal to seasonal changes that fluxes undergo during the active emission period. Climate change will affect all three of these variables in diverse ways. These climate effects will be either "direct" or "indirect," using as a criterion whether or not effects on emissions are the result of repercussions of climatic change on other controlling variables in the environment. Direct climate effects include the immediate influence on fluxes of changes in precipitation (both total amounts and the timing of rainfall) and temperature (such as changes in annual averages and seasonal distributions). Precipitation (assumed to have effects primarily by influencing inundation) and temperature are the primary environmental factors controlling flux. Emission rates themselves are likely to be quite sensitive to changes in either one. For example, wetland areas emitting CH_4 are dependent in large part upon precipitation to maintain soil moisture levels. The periods over which emissions occur are also clearly linked to both temperature and the period of soil saturation. Most attempts to predict effects of climate change on CH_4 emissions have to date been restricted to a subset of possible direct climate effects.

Indirect effects of climate change are those that are mediated through other variables. Indirect effects are likely to be more complex and less straightforward. Although we can make educated estimates for the direct effects of changes in temperature and precipitation on flux for at least several wetland environments based on published correlations (e.g. Harriss & Frolking 1992, Roulet et al. 1992b), including the effects of indirect climate change is much more difficult. For example, an indirect effect on flux would include changes in the frequency and severity of natural fires in northern areas. Such burning would both release CH_4 during the fires and create relatively rapid large-scale landscape changes. Changes in actual evapotranspiration (AET) are also likely to be critical to runoff and moisture levels in many wetlands and therefore also critical to CH_4 flux (e.g. Dooge 1992, Hinzman & Kane 1992). AET is a complex function of precipitation, temperature, vegetation species and vegetation dynamics. Our ability to anticipate and quantify indirect climate effects on flux is limited by both the depth and breadth of our understanding of wetland environments.

Variations in climate are likely to result in changes in both the extent of wetlands and in their annual active period for emissions as well as in other environmental variables that will have different impacts on the spatial distribution and temporal biological activity of wetlands. For northern wetlands, changes in precipitation within a wetland catchment will be critical in determining the extent of a wetland. However, for non-riverine wetlands (the dominant type at northern latitudes), AET and the presence and depth to permafrost are also crucial (Hinzman & Kane 1992). Because permafrost impedes soil drainage, decreased ponding of soils due to melting of near-surface permafrost may become a widespread phenomenon under warmer climates. Alternatively, depending upon topography, the collapse and subsidence of soils due to permafrost melting may enhance ponding in some areas. For riverine wetlands, in most cases associated with water bodies, depth to permafrost (if present) is already significantly greater than the depths at which methanogenesis occurs. Because riverine wetlands integrate hydrologic effects over larger spatial scales, cover type and its impact on AET at a particular site is less critical. Regional or catchment-scale AET effects on water levels, however, are still important.

Since temperature provides the major seasonal signal in the far north, changes in temperature will likely be the most critical variable determining the active season within these wetlands. Temperature change will both alter the length of the active season and the average temperature during that time. Seasonal changes in precipitation and AET are also important since the relative balance between summer and winter precipitation is critical. Because most winter precipitation to a frozen wetland is lost as spring runoff while ground surfaces are still hard, the interaction between snowmelt, temperatures and soil infiltration is vital to determining inundation levels.

In addition to climate variability, human impacts due to population increases and industrial, agricultural and silvicultural development will contribute to change in CH_4 emissions from wetlands. Although these impacts are likely to be concentrated in the tropics and the developing world in the future, human impacts on wetlands in the north may become important especially if these areas become warmer and/or drier.

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