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Role of the Hudson Bay lowland as a source of atmospheric methane

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Abstract. Based on point measurements of methane flux from wetlands in the boreal and subarctic regions, northern wetlands are a major source of atmospheric methane. However, measurements have not been carried out in large continuous peatlands such as the the Hudson Bay Lowland (HBL) (320,000 km^2) and the Western Siberian lowland (540,000 km^2), which together account for over 30% of the wetlands north of 40°N. To determine the role the Hudson Bay Lowland as a source of atmospheric methane, fluxes were measured by enclosures throughout the 1990 snow-free period in all the major wetland types and also by an aircraft in July. Two detailed survey areas were investigated: one ($\approx$900 km^2) was in the high subarctic region of the northern lowland and the second area ($\approx$4,800 km^2) straddled the Low Subarctic and High Boreal regions of the southern lowland. The fluxes were integrated over the study period to produce annual methane emissions for each wetland type. The fluxes were then weighted by the area of 16 different habitats for the southern area and 5 habitats for the northern area, as determined from Landsat thematic mapper to yield an annual habitat-weighted emission. On a per unit area basis, 1.31 ± 0.11 and 2.79 ± 0.39 g CH_4 m^{-2} yr^{-1} were emitted from the southern and northern survey areas, respectively. The extrapolated enclosure estimates for a 3-week period in July were compared to within 10% of the flux derived by airborne eddy correlation measurements made during the same period. The aircraft mean flux of 10 ± 9 mg CH_4 m^{-2} d^{-1} was not statistically different from the extrapolated mean flux of 20 ± 16 mg CH_4 m^{-2} d^{-1}. The annual habitat-weighted emission for the entire HBL using six wetland classes is estimated as 0.538 ± 0.187 Tg CH_4 yr^{-1} (range of extreme cases is 0.057 to 2.112 Tg CH_4 yr^{-1}). This value is much lower than expected, based on previous emission estimates from northern wetlands.

Introduction

The concentration of atmospheric methane (CH_4) has doubled over the last 200 years. It is currently 1720 ppb(v) and is increasing at a rate of between 0.8 and 1.0 % yr^{-1} [Intergovernmental Panel on Climate Change (IPCC), 1990]. To maintain the current concentration and rate of increase, between 505 and 550 Tg CH_4 [Crutzen, 1991] should be emitted annually from all sources. In the present estimates, approximately 20% of the CH_4 is provided by each of wetlands, ruminants and termites, rice paddies, with the remaining 40% from human activities such as coal and natural gas extraction, the transport of natural gas and landfills [Fung et al., 1991], but these estimates have considerable uncertainities.

Wetlands have received much attention because they are the largest natural source [Fung et al., 1991]. Estimates of the present-day source strength for wetlands vary between 80 [Aselmann and Crutzen, 1989] and 115 Tg CH_4 yr^{-1} [Matthews and Fung, 1987; Fung et al., 1991]. The first global estimate set the net emissions for wetlands north of 40°N at 70 Tg CH_4 yr^{-1} [Matthews and Fung, 1987], but later estimates were lower, ranging from 22 [Aselmann and Crutzen, 1989] to 35 Tg CH_4 yr^{-1} [Fung et al., 1991]. These estimates are all based on flux measurements taken outside the two most extensive wetlands in the north: the Hudson Bay lowland (320,000 km^2 [Cowell, 1982] and the Western Siberian lowland (540,000 km^2 [Botch and Masing, 1983]. These two wetlands comprise over 30% of all wetlands north of 40°N.

The purpose of this paper is to estimate the role of the Hudson Bay lowland (HBL) as a source of atmospheric methane using data from the ground and aircraft surveys undertaken during the 1990 Northern Wetlands Study (NOWES) [Roulet et al., 1992a]. A hierarchical linear model based on the areal coverage of wetland types derived from Landsat thematic mapper (TM) is used to extrapolate point flux measurements within two survey regions of $\approx$4800 and $\approx$900 km^2 each. Methane emitted from the entire HBL is estimated using surface flux measurements from both peat and open water surfaces [Hamilton et al., this issue; Holland, 1992; Klinger et al., this issue; Moore et al., this issue] and the areal coverage of wetlands obtained from ecological studies [Riley, 1982]. The average methane flux was also obtained for several weeks in July by airborne eddy correlation measurements [Ritter et al., this

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issue]. These data will serve as a comparison for the extrapolated enclosure estimates.

The HBL is a unique environment for the study of methane emissions because of its areal extent, its almost continuous coverage of peat, and the sequential manner in which the peatlands have developed. Isostatic emergence of the coastlines of James and Hudson Bays over the last 8000 years has resulted in a general sequence of wetlands from saltwater marshes of several hundred years of age at the coast to large complex peatland ecosystems of over 5000 years of age in the interior of the HBL [Riley, 1982]. The measurement program utilized this pattern to examine how methane emissions change along a 140-km transect that represents 5000 years of peatland development and contains most of the wetland types of the high boreal and subarctic climate regions.

Study Area

The Hudson Bay Lowland

The climatology, ecology, and physical characteristics of the HBL are summarized by Mortsch [1990]. The lowland lies between 50° to 58° N latitude and 77° to 94° W longitude (Figure 1). Approximately 265,000 (83%), 47,500 (15%), and 7,000 km^2 (2%) of the HBL are located in the provinces of Ontario, Manitoba, and Quebec, respectively. The HBL encompasses four

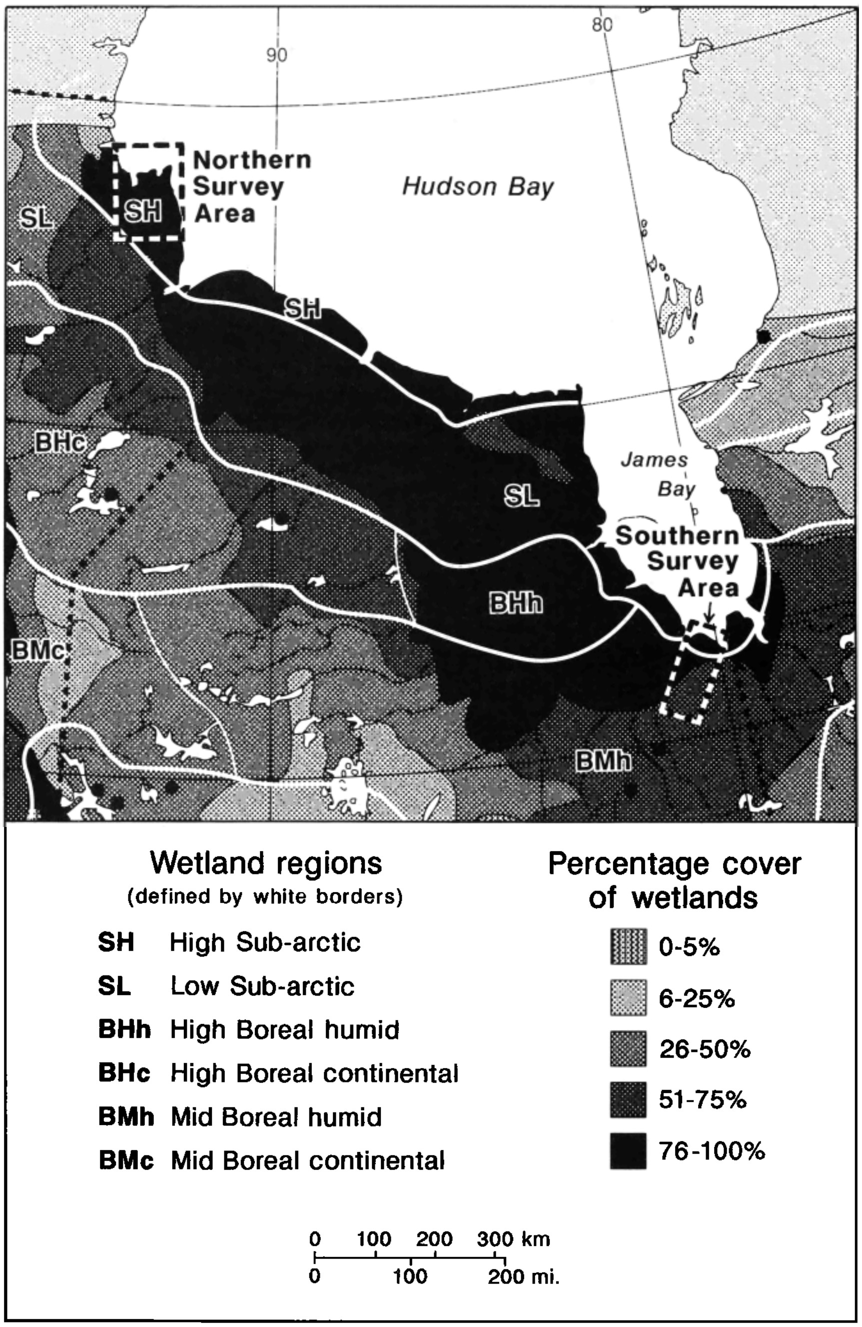

Fig. 1. The ecoclimatic regions of the Hudson Bay lowland (HBL) and the two survey areas.

ecoclimatic wetland zones: the humid mid (BMh) and humid high boreal (BHh) and the low (LSA) and high subarctic (HSA) regions [National Wetlands Working Group (NWWG) 1988]. These regions are defined largely on the basis of January and June mean monthly air temperature and annual precipitation: BMh, January -15° to -23°C; June, 13° to 18°C and 650 to 1000 mm; BHh, January -23° to -25°C; June 12° to 14°C, and 600 to 800 mm; LSA, January, -23° to -30°C; June 14° - 17°C and, 300 to 500 mm; and HSA, January, -26° to -30°C; June, 10° to 16°C, and 250 to 350 mm. Over 70% of the HBL is in the low subarctic zone. The HBL extends from the zone of continuous permafrost along the Hudson Bay coast through the widespread discontinuous permafrost zone to the region where permafrost is absent [Mortsch, 1990].

Over 80% of the lowland is covered by 1 to 3 m deep organic fibrisols and mesisols (peats), which overlie glaciomarine silts and clays laid down during the marine inundation of the post glacial Tryell Sea [Martini, 1989]. The maximum elevation of Lowland is less than 150 m above the mean average sea level (m.a.s.l.) and the topographic gradient from the southern perimeter to the coast is between 0.5 and 1.0 m km^{-1} (< 0.1%).

Mean annual temperatures for Moosonee and Churchill at the southern and northern extremes of the HBL are -1.2° and -7.2°C, while the mean July temperatures are 15° and 12.5°C [Mortsch, 1990]. Approximately 800 mm of precipitation falls annually in the south and 400 mm in the north: ≈ 50% of this is snow. Maximum monthly precipitation occurs between June and October (≈ 50 to 80 mm month^{-1}). The 1990 snow-free period climate for the southern portion of the HBL was not atypical [Mortsch, 1991]. The departure in the 1990 mean monthly temperatures from the 1932 to 1989 mean ranged from a minimum of -1.8°C in September to a maximum of 1.6°C in July. The pattern of precipitation was abnormal: in June, precipitation was 200% of the long-term mean, while in July it was 72% of normal. With the exception of June however, all monthly precipitation totals were within one standard deviation of the 1932-1989 mean. In the northern portion of the HBL the snow-free period in 1990 was relatively normal with average temperatures 0.6°C higher and precipitation 4% greater than the 30-year means.

The distribution and ecology of the wetlands in the Ontario portion of the Lowland has been documented by Riley [1982, 1988]. The wetlands of the Manitoba and Quebec portions of the lowland have received little attention. North of 52°N, bogs and poor swamps dominate except in the high subarctic zone along the coast where the marshes, thicket swamps, and fens are more common [Mortsch, 1990]. In the southern portion of the HBL, marshes dominate the coast but are replaced by fens and then bogs farther inland. Many of the inland peatlands, ≈ 20 to 30 km from the coast, are covered with numerous small pools which in some cases occupy as much as 30% of the peatland surface.

Based on Riley's [1982] work, the coverage of the major wetland types for the Ontario portion of the HBL is estimated in Table 1. In all regions, open or treed bogs dominate, with fens being the second most common wetland type. Throughout the HBL, uplands form between 11 and 23% of the cover. The uplands have no cover of peat.

Survey Areas

Two areas of the HBL were selected for detailed surveys of the CH_4 flux using enclosures and for ecological characterization using remote sensing. The main survey area was located approximately 75 km north of Moosonee, Ontario, in the southern end of the James Bay basin (Figure 1). Six locations were surveyed along a transect that extended 100 km inland from the west coast of James Bay (51° 30'N, 80° 28'W) to Kinosheo Lake (51° 35'N, 81°48'W) [see Glooschenko et al., this issue, Figure 2]. This transect will be referred to as the NP-KL transect. The NP-KL transect begins in the low subarctic zone and terminates in the mid boreal zone. At each location up to six sites, representing most of wetland types of the subarctic and boreal regions, were sampled (Table 2). Site selection was based on the wetland types described by Riley [1982] and the classification of each site was verified by botanical surveys conducted by J. Riley (personal communication, 1990) during the 1990 experiment.

All measurements in the northern survey area were carried out in the vicinity of Churchill, Manitoba (58° 45'N, 94° 09'W) which is located on the southwestern shore of Hudson Bay. The region is underlain by continuous permafrost and has little local relief. Wetlands comprise fens, bogs, marshes, and shallow ponds and lakes which are from 0.25 to 2 m deep. The vegetation in the study area is a combination of both tundra and boreal species. A more detailed description of the wetlands of this region is found in Holland [1992].

TABLE 1. Percent cover of different wetlands of the Ecoclimatic Regions of the Ontario Portion of the Hudson Bay Lowland Derived from Riley [1982] and the National Wetland Working Group [1988]

Wetland Region	Midboreal	High Boreal	Low Subarctic	High Subarctic
Area, km^2	70,640	41,070	137,448	16,026
Marshes	4	4	3	8
Open fens	3	9	19	26
Treed fens and swamps	31	25	10	5
Open bogs	16	28	26	17
Treed bogs	23	22	25	26
Dry uplands	23	11	18	20

TABLE 2: Classification of the Wetlands Sampled for CH_4 flux in the Southern Survey by Riley [1982; 1988], the Ontario Centre for Remote Sensing (OCRS) (See Text), and the corresponding Wetland Classified by the Canadian Wetland Classification System [NWWG, 1988]

Chambers per Type	Riley [1982] Classes	OCRS (1990) Landsat Classes	HBL Classes	Canadian Wetland Classification System
		Marshes		
8	coastal supertidal meadow	supertidal	marsh	Coastal low/tall rush - sedge
	mudflats	mudflats	marsh	tidal water
	coastal supertidal low shrub	supertidal	marsh	coastal low/shrub
4	coastal intertidal	intertidal	marsh	coastal high/sedge
	freshwater		marsh	shallow basin/ graminoid
	shrub rich	shrub	marsh	shallow basin/shrub
	low shrub meadow		marsh	
		Fens		
26	open graminoid	open without pools	open fen	horizontal/ sedge
6	treed	treed	treed fen	stream/treed
12	treed low shrub	treed	treed fen	horizontal/ conifer
12	open graminoid with pools	open with pools	open fen	ladder or northern Ribbed/sedge
14	pools	nc	nc	shallow water/pools
		Swamps		
0	thicket	shrubs	swamp	stream/shrub
0	conifer	conifer forest and swamp	swamp	flat/treed
		Bogs		
19	open lichen rich low shrub	shrub	open bog	domed/lichen
23	open graminoid	open	open bog	flat/sedge
8	open *Sphagmun* rich	open	open bog	domed/moss
13	treed	treed	treed bog	plateau/treed
13	open with pools	open with pools	open bog	domed/low shrub
6	pools	nc	nc	shallow water/pools

TABLE 2 (continued)

Chambers per Type	Riley [1982] Classes	OCRS (1990) Landsat Classes	HBL Classes	Canadian Wetland Classification System
		Lakes		
6	Nc	Water	nc	nc
		Uplands		
4	Aspen	nc	upland	nc
8	Conifer upland	Conifer forest and swamp	upland	nc

Here, nc signifies not classified.

Methods

To estimate the total amount of methane emitted from the HBL, flux measurements were made from all the major wetlands in the northern and southern survey areas. For the two survey areas these measurements are weighted using the fractional coverage of each wetland type obtained by remote sensing. For the flux estimate from the entire lowland, a combination of coverage estimates from remote sensing and ecological surveys was used.

Determination of the Methane Flux

Detailed descriptions of the methods used to obtain the methane flux data from the southern and northern peatlands are given by Hamilton et al. [this issue], Klinger et al. [this issue], Moore et al. [this issue] and Holland [1992]. Over 80% of the flux measurements were obtained using a rigid polycarbonate static chamber (volume = 18 L; area = 0.053 m^2 [Moore et al., this issue; Holland, 1992]). Fewer peatland fluxes were obtained using flexible FEP Teflon bags supported by aluminum frames (area = 0.44 m^2) [Klinger et al., this issue]. The pond fluxes were calculated from surface water CH_4 concentrations and a continuous record of wind speed [Hamilton et al., this issue] using the stagnant film boundary layer model and gas transfer coefficients determined by the method described by Wanninkhof et al. [1990]. The duration of chamber flux measurements varied from 30 minutes to 2 hours, while up to five samples of water were taken over a 24 hour period for the calculation of the pond flux. Each type wetland contained at least two chambers but usually five chambers. The distribution of the chambers among 16 different wetland site types is outlined in Table 2. Six sample sites were used in the northern survey. For the pond fluxes, between 5 and 15 ponds were sampled at each location on the NP-KL transect. These data were averaged to produce one flux for a location. The flux from ponds in the northern survey area was obtained using chambers. A large proportion of the methane samples were analyzed on two Shimadzu Mini-2 gas chromatographs equipped with flame ionizer detectors [Hamilton et al., this issue; Moore et al., this issue]. A small number of the southern samples were analyzed on a baseline 103A gas chromatograph [Klinger et al., this issue]. The samples from the northern survey were shipped to Montreal in vaccutainers and analyzed on a Perkin Elmer 3920 FID gas chromatograph. Gas chromatograph calibrations and data quality control are discussed [Klinger et al., this issue; Moore et al., this issue]. The minimum flux detectable by the combination of the polycarbonate chambers, the Shimadzu Mini-2, and a 2 hour flux run is 0.1 mg CH_4 m^{-2} d^{-1}. The mimimum for the teflon chamber and the Baseline 103A and the Churchill fluxes was 1.0 mg CH_4 m^{-2} d^{-1}. The lowest detectable flux from the ponds is a function of wind speed and CH_4 concentrations and is therefore variable, but at the average wind speed it is 0.1 mg CH_4 m^{-2} d^{-1}.

In total over 1800 flux measurements were obtained in the southern survey area between June and October and 976 fluxes from the northern survey between June and September. The respective sampling periods for both surveys represent a period when the peatlands were snow free.

The vertical flux of CH_4 was also obtained via an airborne eddy correlation technique during July [Ritter et al., this issue]. Fast response ($\approx$ 20 s s^{-1}) measurements of CH_4 and the ambient vertical velocity were made. The turbulent air motion measurement system (TAMMS) was used on the NASA Electra aircraft for measuring the lateral, longitudinal, and vertical turbulent air velocity components needed for eddy correlation flux measurements [Ritter et al., 1993]. The sensors used for making flow angle measurements (rotating balsa vanes) as well as those for pressure, air temperature, and fast response water vapor measurements (Lyman alpha hygrometer) were located near the tip of a 3.7-m boom on the nose of the Electra. Fast response CO and CH_4 measurements were provided by a tunable diode laser (TDL). The laser beams of two TDLs (one lasing in the 4.7-μm CO band and a second in the 7.6-μm CH_4 band) are combined and are then directed along a 10 m folded optical path enclosed in a 1.5-L white cell. Further details on the specifications of this instrument can be found in the work of Sachse et al. [1991].

Determination of the Areal Coverage of Wetlands in Survey Areas

The areal extent of each wetland type was needed to extrapolate the methane fluxes. Two approaches were taken to the classification of the wetlands of the HBL. In the two survey areas, wetlands were classified by the Ontario Centre for

Remote Sensing using Landsat-TM. For the extrapolation of the fluxes to the entire HBL, the use of Landsat-TM was cost prohibitive. Fortunately, the surveys conducted by Riley [1982] were sufficiently extensive that they gave detailed coverage but at a coarser resolution. Riley sampled 335 different areas in the Ontario portion of the HBL yielding a sample area of ≈750 km^2. The effect of the aggregation of wetlands into broader classes on the regional estimate of methane emissions is examined in the results section.

Landsat-TM digital satellite image data recorded on August 6, 1990, was used for the analysis. A Landsat full frame, a rectangular array of 5700 image lines, each containing some 6300 pixels, covers an area of approximately 185 x 171 km (> 31,000 km^2). For each 30 x 30 m pixel, reflectance for seven discrete wavelengths in the visible and near infrared portion of the electromagnetic spectrum is recorded. A portion of the full Landsat scene, covering the NP-KL transect (40 x 120 km: 4800 km^2) was registered to the 1:50,000 NTS map sheet. This produced a new set of digital files encoded with universal transverse mercator (UTM) coordinates, measuring 1600 lines of 4700 pixels, each pixel having a size of 30 x 30 m.

From these data an infrared, red, and green band were used to produce a false color infrared image used for vegetation classification. On the basis of field observations and past experience [eg. Pala and Boissonneau, 1982] in interpreting false color composite satellite images, representative (training) areas of significant land cover classes were selected within the transect. Field verification was done by botanical surveys conducted during the NOWES (J. Riley, personal communication, 1990). Twenty-one classes were selected. Statistical description of the spectral properties of the representative areas (i.e., spectral signatures) were used by a maximum likelihood classifier to create a classified image by assigning each pixel one of 26 cover classes.

The information contained in the Landsat data was modified to distinguish between spectrally similar classes on the basis of shape, distribution, contextual information, association and location within the landscape. This process yielded 26 classes, and these were merged by similar aspects relevant to the exchange of trace gases, such as vegetation type and surface wetness, to yield a final 16 classes used in the extrapolations. Three sets of cover statistics were produced: (1) the fractional component of each of the 16 wetland types for the NP-KL transect; (2) the fractional component of each wetland for 24 bands (5 km deep and 40 km wide) running parallel to the coast of James Bay from the coast inland to Kinosheo Lake; and (3) the fractional component of each wetland type for eight sub-transects consisting of 192 5 x 5 km squares.

Landsat-TM has a pixel size of 30 x 30 m. While this resolution is sufficient to identify the abundance of the major wetland ecosystems, including bogs and fens that have a large enough portion of their surface covered with water to affect the spectral signature, it is insufficient to determine the actual percent coverage by surface water when the pools are smaller than ≈900 m^2. In 1989 and 1990, color air photography was flown in July for the sample locations in the southern survey area. Flight lines followed the transect at a nominal altitude of 3000 m. A 152-mm lens was used on a Wild RC 10 mapping camera, giving a scale of 1:20,000. From this air photography, pools down to a radius of 2 m, or an area of approximately 15 m^2, could be resolved. The percentage of the surface of the wetlands which contained pools was determined for the six locations along the NP-KL transect. When a Landsat pixel was identified as being in the classes of open bogs with pools, or open fens with pools, the percent of pool coverage analyzed using the air photography was applied to that pixel.

A Landsat-TM scene, recorded on August 2, 1984 was used to analyze a 900 km^2 area centered on Cape Churchill in the northern portion of the HBL. The image used was taken prior to the flux measurements, but the rate of landscape change in northern peatlands and the permaforst region are extremely slow [e.g. Mortsch, 1990] so that the errors attributed to the flux measurements themselves are probably much larger than those introduced by the 6-year difference. A thematic map and cover statistics of the 16 main cover types was produced using the same methods described above, but the analysis was based on ground truthing in the Ontario portion of the HBL and not in the Churchill area. Therefore the same level of accuracy as the southern transect cannot be guaranteed for the northern portion of the HBL.

Extrapolation of the Fluxes

A simple linear model was used to extrapolate the fluxes from their point of measurement to the regional scale. For the detailed survey areas the annual methane emission for a given wetland type is obtained by integrating the mean daily flux through time. The annual habitat-weighted methane emission is obtained by multiplying the annual methane emission for each wetland type by the area of that wetland type. The standard error of the extrapolated flux was calculated using a linear combination of errors [Barford, 1985] that were weighted by the square of the fractional area of the particular wetland type. The standard error is used in the analysis of errors where possible in this paper, because it provides a better estimate of accuracy of the mean than does the standard deviation [Barford, 1985].

For the detailed survey areas, up to 12 classes of the wetlands and landscape units are used in extrapolations. Five wetland classes and one upland class are used to determine the annual habitat-weighted methane emission for the entire HBL.

Results

Wetland Coverage

Sixteen wetland/land cover types were identified along the NP-KL transect using the Landsat-TM (Table 3; Plate 1). Treed, shrub-rich

TABLE 3. Sixteen land cover classes Obtained by Landsat Thematic Mapper by the Ontario Centre for Remote Sensing

Land Cover Type	Percent Cover	Flux Measurements
Water	8.62	yes
Marl lakes	0.01	no
Mudflats	1.38	no
Intertidal marshes	0.54	yes
Supertidal marshes	0.79	no
Shrubs	3.99	yes
Open fen	10.74	yes
Open fen with pools	7.34	yes
Shrub-rich treed fen	18.51	yes
Treed fen/spruce	12.40	yes
Open Bog with pools	4.97	yes
Open Shrub-rich bog	3.57	yes
Open lichen-rich bog	4.86	yes
Treed bog and swamp	14.66	yes
Conifer forest/swamp	5.91	yes
Recent burn	0.63	no
Unclassified	1.08	no

fens, and open fens (with and without pools) dominate the transect, particularly over the first 50 km (Figures 2a and 2b). Open bogs and treed bogs appear approximately 20 km inland and cover an area equal to that of the fens by 50 km inland (Figures 2a and 2b). The fractional components of wetland types along the transect are slightly biased toward fens when compared to the ecological surveys of Riley [1982], because a portion of the transect (≈ 20% of the first 30 km) incorporates a rich, treed fen that surrounds the Moose River valley. While these fens are a significant wetland type in the vicinity of large rivers, they are relatively insignificant in the HBL.

In the first 20 km of the transect a small fraction of the open fens and very few open bogs are identified as having surficial pools (Figures 2a and 2b). However, beyond 40 km inland, over 40% of the open fens and 30% of the open bogs are inundated. From the analysis of the color air photographs the surface area of fens occupied by pools changed from less than 5% at 10 km inland to near 40% at 30 km inland. Inland of this point, the mean area of standing water at the time of color photography for open fens and bogs was 31 and 41%, respectively, with the exception of two large patterned fens where the inundation was in excess of 80%.

The wetland composition of the northern survey area is given in Table 4. The most notable difference between the northern and the southern surveys is a greater area of nonwetland-type landscape in the north: ≈40%. The dominant wetland type was open fen. The coverage of forested wetland in the north is very low compared to the south.

Methane Flux from Survey Wetlands

In Table 5 the characteristics of the annual mean daily methane flux from the wetlands of the southern survey area are summarized. The mean methane emissions are much lower than those observed for isolated wetlands in other northern regions [cf. Crill et al., 1988; Moore et al., 1990; Sebacher et al., 1986; Whalen and Reeburgh, 1988], especially the very low flux from fens. For all wetlands the mean flux was between 2 and 30 times larger than the median flux, indicating the frequency distribution of fluxes was skewed to smaller fluxes (Figure 3). For five of the wetland types the mean flux was greater than the 75% quartile. The variance observed in this survey is similar to that obtained in other regional surveys [Bartlett et al. 1989; Moore et al., 1990].

The statistical summary presented in Table 5 is for the sampling season that extended from June to October. There was no sampling in the winter when the peatlands were frozen. Dise [1992] has shown that winter methane fluxes can comprise between 8 and 21% of the total annual flux for peatlands on the southern fringe of the boreal forest zone. However, winter temperatures in the southern HBL (January mean monthly temperature (JMMT) = -20.4°C [Mortsch, 1990]) is more similar to that of central Alaska (JMMT = -22.9°C [Ruffner and Bair, 1985]) where Whalen and Reeburgh [1988] observed little winter flux of CH_4, than that of northern Minnesota (JMMT = -12.9°C; [Ruffner and Bair, 1985]) where Dise [1992] worked. Because frost penetrates well into the

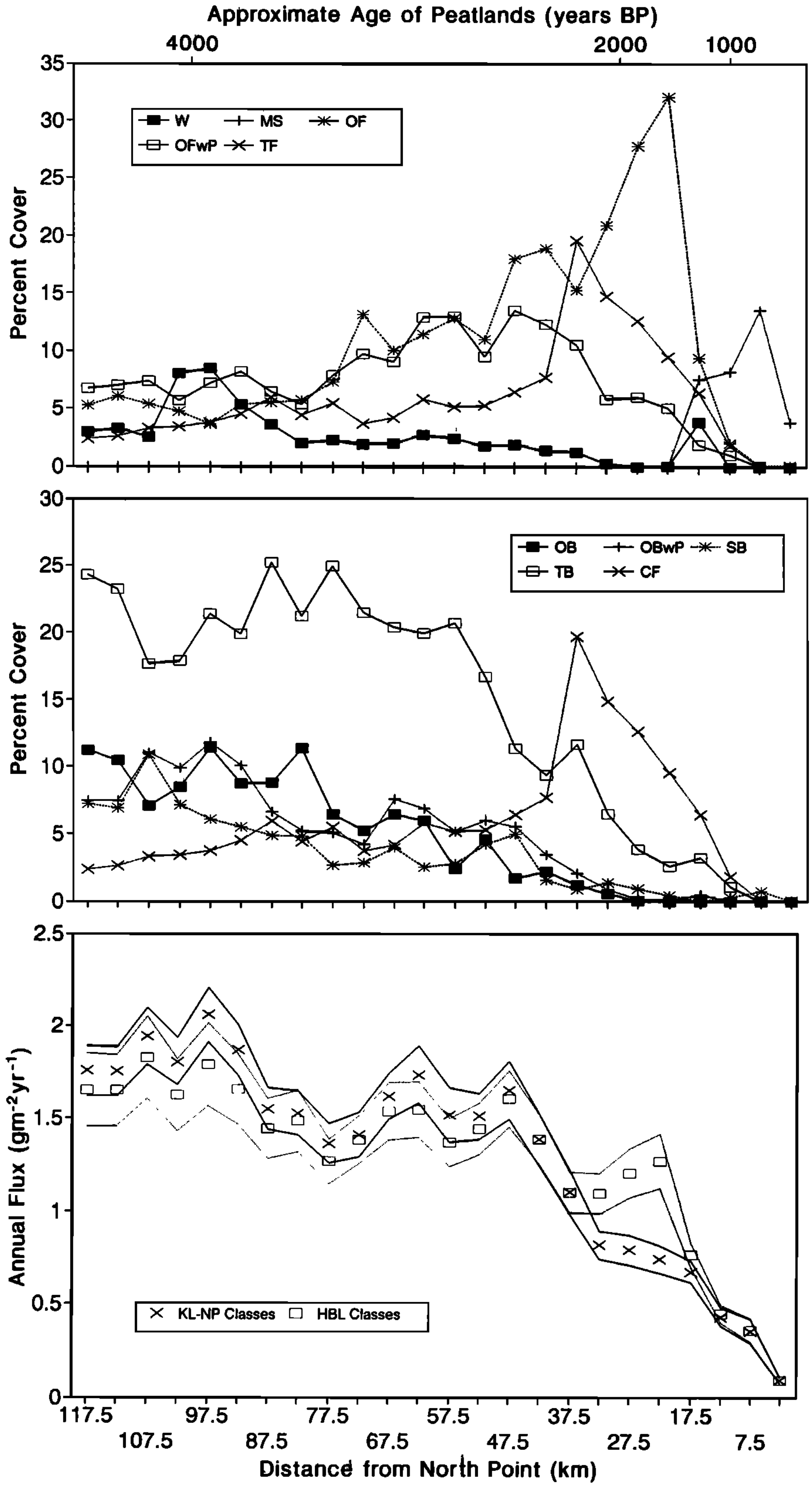

Fig. 2. (a) Percent coverage of the fens and marshes along the NP-KL transect. W, water; MS, marsh; OF, open fen; OFwP, open fen with pools; and TF, tamarack. (b) Percent coverage of the bogs and forests along the NP-KL transect. OB, open bog; OBwP, open bog with pools; SB, shrub rich bog; TB, treed bog; and CF, conifer forest/uplands. (c) Annual habitat-weighted methane emissions along the NP-KL transect. The solid curve indicates the standard error of the estimated flux using the KL-NP classes, while the soild line indicates the errors using the HBL classes.

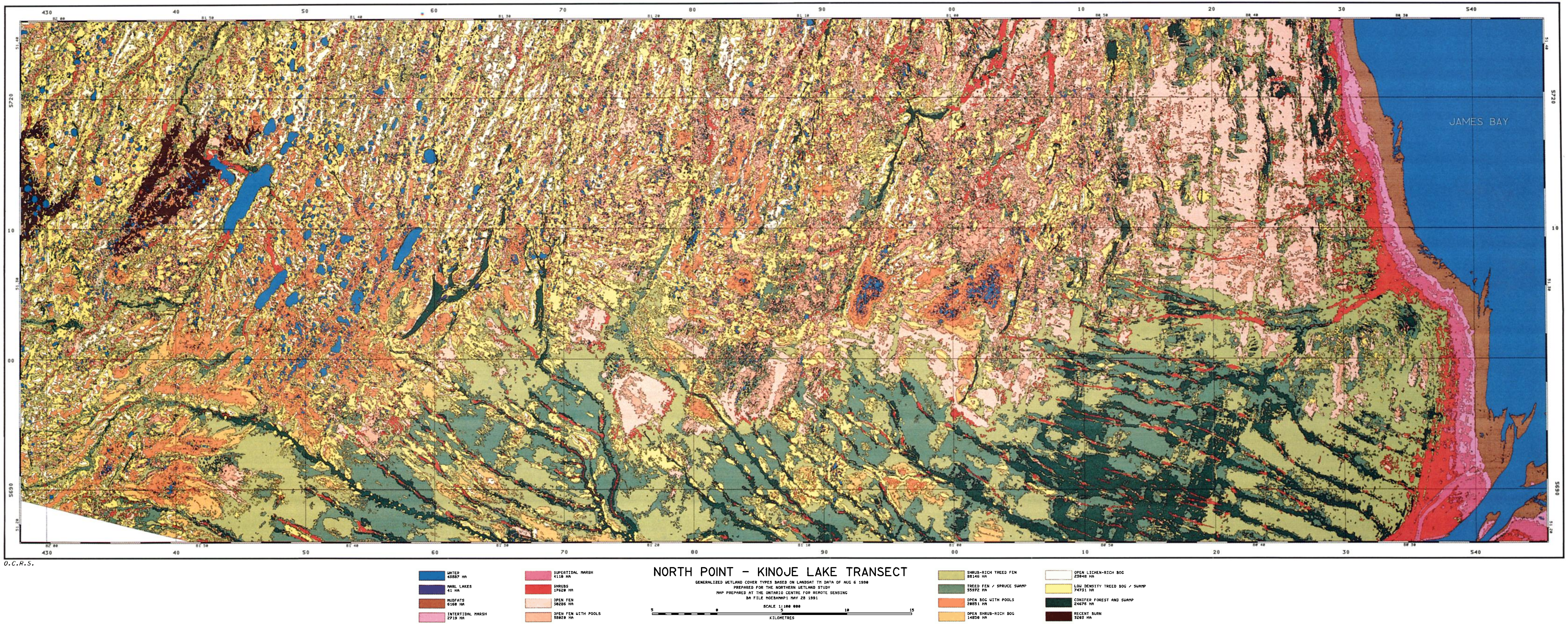

Plate 1. False color map of the 16 wetland/landscape classes determined from an August 4, 1990, Landsat-TM image. Data processed at the Ontario Centre for Remote Sensing.

TABLE 4. Areal Extent of Wetlands in the Northern Survey Area on Cape Churchill As determined by Landsat-TM for a 774.3 km^2 Area

Landcover Type	Percent Cover	Flux Measurements
Coastal marshes	1.2	Yes
Shallow lakes	5.9	Yes
Open fen	48.4	Yes
Treed bog	4.1	Yes
Forest/woodland	15.4	No
Rock outcrop	2.5	No
Upland	22.5	No

TABLE 5. Annual Mean Daily Methane Flux From Wetlands on Southern Transect.

Land Cover	Mean	Standard Error	Max.	Min.	Median	Q1	Q3	N	F_{PT}
Water	12.3	2.7	146.0	0.2	3.4	0.5	9.8	87	1.54
Marshes	30.9	6.1	274.5	-2.3	6.2	0.4	43.0	84	2.29
Shrubs, shrub - rich treed, and treed fen	2.5	0.5	32.0	-2.4	0.6	-0.1	3.7	102	0.37
Open fen	7.9	0.9	297.5	-1.6	2.9	0.2	10.1	451	0.66
Fen pools	163.0	-	771.0	15.5	112.0	65.0	172.0	62	13.82
Open bog	53.5	6.7	1355.5	-1.7	11.7	2.7	37.8	514	4.62
Bog pools	110.0	-	930.0	1.4	13.1	3.8	49.5	39	6.08
Shrub-rich bog	47.5	8.5	1626.8	-1.5	4.7	0.1	26.2	329	4.03
Treed bog	1.8	0.8	65.7	-1.7	0.1	-0.2	1.8	127	0.17
Conifer forest	3.3	1.8	49.7	-2.2	0.0	-0.8	2.3	35	0.17

All values with the exception of the annual methane emissions flux for the peatland type, F_{PT}, are in mg CH_4 m^{-2} d^{-1}. The units of F_{PT} are g m^{-2} yr^{-1}. Q1 and Q3 refer to the upper and lower quartile.

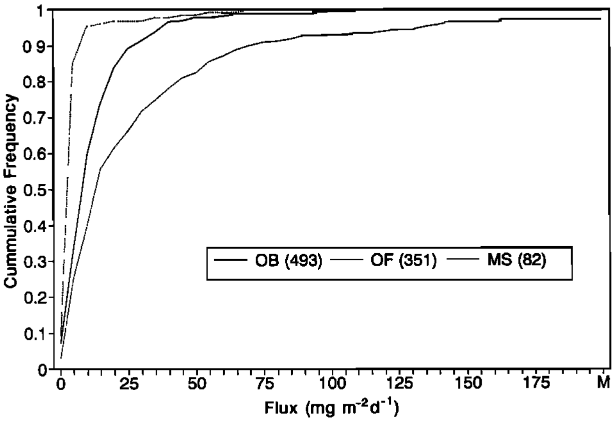

Fig. 3. The frequency distribution for methane fluxes for three different wetlands of the southern survey area (see caption of Figure 2 for wetland codes).

saturated zone of the peatlands of the HBL [Mortsch, 1990], diffusion should be greatly reduced.

The largest methane fluxes, on a per unit area basis, were from the pools in the fens. They were 2 to 20 times larger than the fluxes from the adjacent peat surfaces (Table 5). In contrast the fluxes from the pools in the bogs were more comparable to the adjacent peatland. The pool fluxes were not measured directly like those for the peatlands but were calculated (see methods) which could lead to an overestimate of between 10 and 30% [Kwan and Taylor, 1993]. Regardless of this possible error, the summary statistics for CH_4 flux from the pools in Table 5 clearly show the fluxes from the pools were larger than from the adjacent peat surfaces in the fens. The pool fluxes also showed the same degree of variability and skewed distribution.

A summary of the methane fluxes measured from wetlands in the northern survey area is presented in Table 6. The fluxes were much larger

TABLE 6. Annual Mean Daily Methane Flux From Northern Survey Region.

Land Cover	Mean	Standard Error	Max.	Min.	Median	Q1	Q3	N	F_{PT}
Coastal marshes	84.3	9.7	2255.0	-2.6	43.3	17.5	68.3	270	8.00
Shallow lakes	125.5	15.8	1387.0	0.1	26.6	6.1	139.8	238	10.67
Open fen	78.6	14.2	1585.0	-0.6	24.0	1.9	73.7	293	6.68
Treed bog	0.2	1.0	6.1	-1.0	0.1	-0.3	0.3	175	0.02

All values with the exception of the annual methane emissions for the peatland type, F_{PT}, are in mg CH_4 m^{-2} d^{-1}. The units of F_{PT} are g m^{-2} yr^{-1}.

from two wetlands types than from their southern survey counterpart: coastal marshes, mean flux was 2.7 times larger and the annual emissions were 3.5 times greater; and open fens without pools, mean flux and annual emissions were 10 times larger. The mean daily fluxes from the shallow lakes and treed bogs were comparable to the southern survey. It is not obvious why the fluxes should be larger in the northern portion of the HBL. The duration of warmer temperatures is shorter, but a larger proportion of the northern wetlands were wetter [Holland, 1992] than the southern wetlands [Moore et al., this issue]. Possibly, the presence of permafrost inhibits drainage, maintaining higher water tables. Moore et al. [this issue] and Roulet et al. [1992b] demonstrate that the maintenance of saturated conditions is more critical for higher fluxes than temperature, and only after wetland saturation is satisfied, do peat temperatures become a dominant environmental correlate. Moore et al. [this issue] demostrate that the potential rate of CH_4 production was higher, while the potential rate of consumption was slightly lower, in laboratory incubations of peat from the northern survey area wetlands when compared to the rates obtained for peat from the southern survey area wetlands.

Extrapolation of the Methane Flux Along the NP-KL Transect and Northern Coast

The annual CH_4 emissions observed for the wetlands along the NP-KL transect in the southern area of the HBL (Table 5) was combined with the areal coverage of wetlands and landscape types along the transect (Figures 2a and 2b) to estimate the annual, habitat-weighted methane emission (Figure 2c). The annual emissions along the 140-km transect were calculated using the areal extent of wetlands integrated over 5-km-wide linear strips, parallel to the James Bay coast. The increase in CH_4 emissions is larger over the first 45 km than that of the last 75 km. This increase corresponds to the replacement of treed fens, open fens, and conifer forests by open and treed bogs and wetlands with pools. The annual emissions from the pools themselves decreased from the coastal fens inland to the interior sites [Hamilton et al., this issue]. The mean annual habitat-weighted per unit area emission for the NP-KL transect was 1.313 ± 0.110 g CH_4 m^{-2} yr^{-1}. The standard error in flux along the transect, expressed as a percent of the estimated flux, ranged from 7.3 to 18.9%.

To assess the potential degree of bias introduced in the calculated flux by the large fens of the Moose River basin, the annual emission was recalculated by dividing the 40-km-wide NP-KL transect into eight 5-km-wide subtransects. The change in CH_4 emission from the coast inland to the interior follows the same trend for transects 3 to 8 (the most northwest transects), while the emission from transect 1 and 2 (the most southeast transects and in the Moose River basin) was considerably lower (Figure 4). The mean habitat-weighted emission for transects 1 and 2 was 0.557 and 0.759 g CH_4 m^{-2} yr^{-1}, respectively, while the emission for other transects ranged from 1.133 to 1.785 g CH_4 m^{-2} yr^{-1}. Hence the variability in regional estimates of emissions can be > 40% depending on the location of the survey area even in what appears to be very similar landscapes. The variability in estimates among transects 3 to 8 is < 30%, i.e., the error calculated without the influence of the fens of the Moose River valley. This can be considered solely wetland survey variance because the same flux data were used on each transect and the only variables that changed were the fractional coverage of each wetland type.

Methane Flux From the Hudson Bay Lowland

With a wetland region as large as the HBL the use of Landsat-TM to determine the percent cover of wetland types becomes prohibitively expensive. Fortunately, Riley's [1982] ecological field surveys and analysis of air photography provides an estimate of the wetland coverage for the Ontario portion of the HBL, but there are no reliable data for the Quebec and Manitoba portions of the HBL. The Quebec portion of the HBL lies entirely within the same ecoclimatic region as that of the NP-KL transect, therefore data from the southern survey was assumed to be

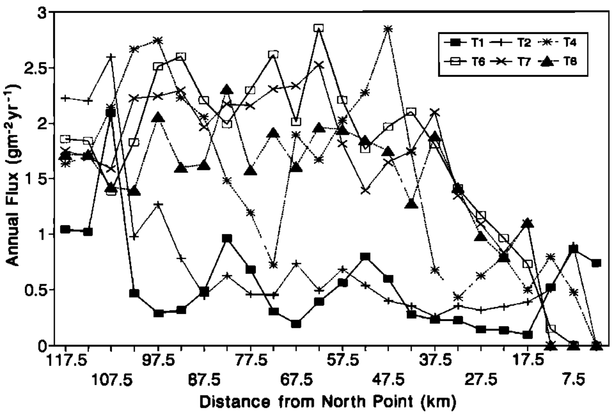

Fig. 4. Annual habitat-weighted methane emissions for six 5 x 120 km subtransects of the NP-KL transect (two transects were emitted to enhance clarity) (see Figure 2 caption for wetland codes).

representative for that portion. The larger Manitoba portion of the HBL is in a very different climate region, as indicated by the presence of continuous permafrost. The distribution of wetlands in the low subarctic zone of Manitoba was assumed to be the same as the low subarctic zone in Ontario. The high subarctic region of the HBL is climatically distinct from the low subarctic and boreal regions. Riley's data suggest that there is a smaller proportion of bogs than in the southern regions, and that open peatlands are more prevalent. Comparison of the Landsat cover analysis of the southern and northern survey areas confirms these differences. Open wetlands represent over 50% of the northern survey area, open bogs are not present, and treed wetlands and forests comprise 14 and 5% of the landscape, respectively. In contrast, open wetlands and treed wetland comprise 37% and 46%, respectively, the southern survey area. To incorporate these differences the annual emission of CH_4 from the high subarctic region was computed using the fluxes obtained from the Churchill area (Table 6) and the different proportions of wetlands determined from the 900 km^2 Landsat-TM image of the Cape Churchill peninsula (Table 4).

The results of the flux surveys show that the flux from pools in fens and bogs in both the southern (Table 5) and the northern regions (Table 6) were greater than the adjacent peatland. Because the ecological survey of Riley [1982] did not distinguish wetlands with pools from those without pools, we computed the ratio of the area of fens or bogs with pools to the total area of open fens or bogs from the NP-KL transect and applied that ratio to the entire HBL with the exception of the High Subarctic region. Based on Landsat data, ≈11% of all open fens and bogs contained surface pools, and on the analysis of the color air photography the average surface inundation for an open fen and open bog was 31 and 41% respectively (see section on wetland coverage). For the high subarctic region the pools were treated explicitly as classified in the Landsat-TM image for the Churchill area. This means that small pools (area < 900 m^2) would be classified as a peatland rather than a pool and hence the flux would be underestimated.

The ecological survey of Riley [1982] has a broader level of aggregation of wetland classes and coarser resolution than the Landsat-TM surveys. To test the effect aggregation has on the annual habitat-weighted emission, the emission along the NP-KL transect was computed using the Landsat-TM derived data summarized into the Riley's six classes (Figure 2c). The mean emission using the full Landsat-TM classes was 1.313 ± 0.110 g CH_4 m^{-2} yr^{-1}, while the aggregate wetland classes yielded a mean annual emission of 1.295 ± 0.141 g CH_4 m^{-2} yr^{-1}, representing a 2% difference.

While the above analysis shows aggregation of wetland classes has little effect on the habitat-weighted emission, it does not test if the Riley [1982] estimates of the fractional coverage of each wetland type are good estimates and what size error in the emission might be introduced by using Riley's data. A direct comparison between Riley's coverage fractions and those derived by Landsat-TM can not be done because the southern survey area only makes up a small fraction of the total area surveyed by Riley. However, Riley divided his analysis into ecoclimatic regions, and the NP-KL transect straddles two of these regions: the low subarctic and high boreal wetland regions. Using Riley's percent coverage for these two climate zones (Table 1), the mean habitat-weighted emission is 1.908 and 1.784 g CH_4 m^{-2} yr^{-1}, respectively. The mean emission for NP-KL subtransects 3 to 8 is 1.511 g CH_4 m^{-2} yr^{-1}. The emission, based on Riley's cover data, is between 18 to 26% higher. Sub-transects 3 to 8 were used to avoid the unique influence of the wetlands of the Moose River valley on the regional flux estimates (see Figure 4).

Based on the analyses described above, the total annual CH_4 emission from the HBL in 1990 was 0.538 ± 0.187 Tg CH_4 yr^{-1} (Table 7). If the southern transect data had simply been extrapolated to the entire lowland, the total annual emission would have been 0.420 Tg CH_4 yr^{-1} (15% lower). The single largest wetland contribution is from open bogs (Figure 5). This is due to the combination of higher emissions and the large areally extent of open bogs. Treed bogs and uplands contributed similar amount of CH_4. This is because the water table in the treed bogs was very low (< 40 cm), making the surface extremely dry, while in contrast the upland forests were relatively moist. The median flux from the forest was 0.0 mg CH_4 m^{-2} d^{-1}, suggesting the forest was neither a significant source of CH_4 nor a sink of CH_4 as observed in other forests [e.g. Crill, 1991]. The low subarctic region is the most significant contributor of all the ecoclimatic regions because it occupies by far the greatest proportion of the HBL (Figure 5).

The above estimates are subject to considereable error. First are the errors associated with the flux estimates. These can be quantified in a manner similar to that used for the southern transect. Assuming no error in the areal estimate of the ecosystems, the standard error on the flux of CH_4 from the HBL is 35%. Extrapolating the fluxes by integrating the upper and lower quartile flux estimates from the northern and southern survey areas rather than the mean yields an upper estimate of 3.722 Tg CH_4 yr^{-1} and a lower estimate of 0.057 Tg CH_4 yr^{-1} (Figure

TABLE 7: Annual Habitat-Weighted Methane Emissions (x 10^{-3} Tg CH_4 y^{-1}) for the 1990 Snow-Free Period for the HBL organized by Wetland Type and Ecoclimate Region

Wetland/ Region	MidBoreal	High Boreal	Low Subarctic	High Subarctic	Total by Wetland Type
Marshes	7.1	3.8	12.1	0.1	23.1
Open fens	6.5	10.3	92.3	30.9	140.0
Treed fens	9.1	3.9	6.6	0.3	20.0
Open bogs	57.2	52.9	209.4	12.0	331.5
Treed bogs	3.2	1.6	7.8	0.7	13.3
Uplands	3.2	0.8	5.6	0.6	10.2
Total by region	86.3	73.3	333.8	44.6	538.0

5). These estimates are a factor of 6.9 and 9.4 times, higher and lower than the 0.538 Tg CH_4 yr^{-1} estimated from the time-integrated average flux. A second source of error could come from the incorrect estimate of the coverage of the different types of wetlands. Unlike the error in the fluxes which are statistical random errors, an error in the coverage of one wetland type necessitates an error in at least one additional class, i.e. the errors are not independent. The analysis of fluxes along transect 3 to 8 in the southern survey area suggested that variance in the area classified was ≈ 30%. Assuming that the aggregation of wetland classes into six classes introduces a further 18 to 26% error, the total error for the extrapolated flux could be as large as 0.484 Tg CH_4 yr^{-1} or ≈ 90%. This would increase the overall error in the flux estimate to over 50%. If it is assumed that the entire HBL is covered by the wetland type that yielded the highest amount of CH_4 (open bogs) then the flux for the HBL would increase to 1.472 ± 0.237 Tg CH_4 yr^{-1}, a factor of 2.7 times the mean estimate.

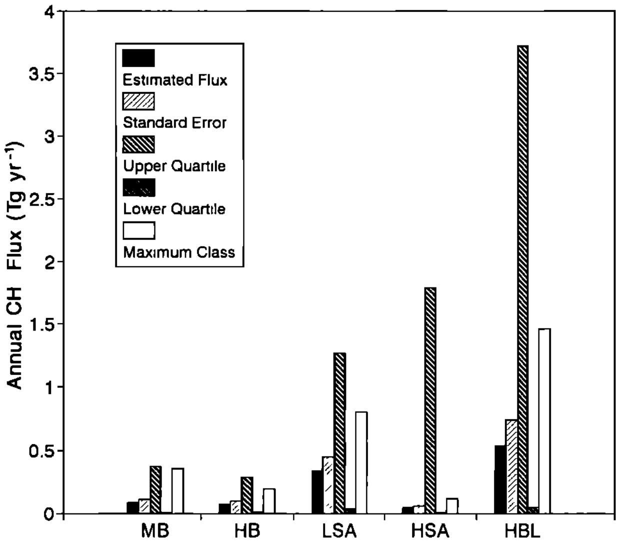

Fig. 5. The distribution of annual habitat-weighted methane emissions (estimated flux) for the different ecoclimate regions of the HBL. Four different error scenarios are also shown. The standard error represents the estimated flux plus one standard error. The upper and lower quartile estimates were derived by habitat-weighting the time-intergrated Q3 and Q1 fluxes for the northern and southern survey sites (see Tables 5 and 6). The maximum class was derived assuming that the entire HBL was covered with the highest emitting wetlands. MB, mid boreal; HB, high boreal; LSA, low subarctic; and HSA, high subarctic.

Comparison of Extrapolations With Airborne-Derived Fluxes

A total of 18 regional CH_4 flux estimates were done between July 11 and July 26 by the NASA Electra. The extrapolation model was also run for this same period for the southern and northern survey areas and the entire HBL, using enclosure and pond flux data obtained between July 11 and July 26. Five aircraft fluxes were obtained over the southern survey with a mean of 14 ± 8 mg CH_4 m^{-2} d^{-1}, while the extrapolation model yielded 16 ± 11 mg CH_4 m^{-2} d^{-1}, representing a factor of 1.1 difference (Table 8). The errors presented here are standard deviations, not standard errors, to facilitate the statistical comparison of the mean fluxes. There is no statistical difference in means based on a student t test ($p = 0.05$) assuming unequal variance [Zar, 1984]. The comparison for the northern survey area is not as good: 12 ± 16 from the aircraft versus 44 mg CH_4 m^{-2} d^{-1} from the extrapolation model, a difference of 3.7. The southern flights were all centered over the Kinosheo Lake area which formed a large portion of the southern survey area, but the northern flights were never directly over the northern survey area at the Churchill, Manitoba

TABLE 8.: Comparison of Aircraft Derived Regional CH_4 Fluxes ($w'CH_4'$) and the Fluxes Determined Using the Extrapolation Model for the Period July 11 - 26, 1990

Flight Leg	Date	Local Time	$w'CH_4'$; mg m^{-2} d^{-1}	Mean of Aircraft Fluxes, mg m^{-2} d^{-1}	Flux From Model mg m^{-2} d^{-1}
Southern Survey Area					
7	7/17	1110	26 ± 6		
	7/17	1225	10 ± 4		
16	7/22	1417	19^*	14 ± 8	16 ± 11
	7/22	1427	7^*		
17	7/26	1112	9 ± 2		
Northern Survey Area					
13	7/21	1317	31		
14	7/21	1331	2	12 ± 16	44.1
15	7/21	1357	3		
Other portions of the HBL					
2	7/11	1548	7		
3	7/11	1605	10 ± 3		
4	7/11	1638	11		
5	7/11	1653	6 ± 3		
6	7/11	1720	15	9 ± 6	
9	7/21	1211	-1		
11	7/21	1226	13 ± 3		
12	7/21	1258	20		
19	7/26	1822	12^*		
	7/26	1829	13^*		
Mean for HBL			10 ± 9		20 ± 16

* Flight level values: these fluxes are based on only one flight level while all others are based on the flux divergence between two flight levels [Ritter et al., this issue].

area. The closest flight line (15) [Ritter, this issue, Figure 2] terminated > 60 km south of Churchill. The standard deviation for the northern flights is much higher than that of the southern flights (coefficient of variation for the northern mean aircraft flux is 133% compared to 57% for the southern survey area), but a direct statistical comparison for the northern survey area is not possible because the sample size is too small (e.g N-1 = 2 for the aircraft flux). One of the flights (13) near the northern survey area, did yield a flux of 31 mg CH_4 m^{-2} d^{-1} which is closer to that of the extrapolated fluxes. The mean aircraft flux based on all 18 flux runs was 10 ± 9 compared to 20 ± 16 mg CH_4 m^{-2} d^{-1} from the extrapolation. These two mean fluxes are different by a factor of 2, but they are not statistically different based on a student t test ($p = 0.05$) assuming unequal variance [Zar, 1984] because there is a large variance associated with each mean. We consider this a confirmation of the extrapolation approach used in this study given the inherent spatial variability of trace gases fluxes.

Discussion

The methane flux from the HBL can be examined at three scales. At a small scale (1 - 100 m^2) the within-site and between-site variability can be related to ecological, chemical, edaphic, and physical differences among sites [Klinger et al., this issue; Moore et al., this issue]. At the mesoscale (1 - 1000 km^2) the seasonal methane emissions can be examined in relation to the development of the landscape. In the case of the HBL, because of the sequential development of the landscape represented by the changing importance of various wetland types, the temporal changes in methane flux over several thousand years can be inferred. Finally, the significance of the whole HBL as a source of atmospheric methane can be determined. The latter is important in the calculation of global methane budgets because of the areal extent of the lowland.

The change in methane flux along the southern transect displayed a pattern related to the development of the HBL. Previous studies have examined fluxes from different wetland types which were at different stages of succession [e.g. Crill et al., 1988; Moore et al., 1990; Roulet et al., 1992b] but there has been little attempt to place the measured fluxes in the context of the development of a peatland landscape. There is a very large body of literature on peatland formation and evolution (see Glaser [1987] for review). Klinger et al. [this issue] look at the change in methane flux along one successional sequence of the HBL. The HBL is a paludified landscape: the continuous peatland has formed by the coalescence of many individual peatlands that have evolved along several different successional routes [Riley, 1982]. At the scale of the southern transect the various routes of succession result in a shift from the predominance of marshes and fens to more bogs and treed wetlands inland. This transect also represents a chronosequence of 4000 years. The combination of three different patterns result in the overall pattern of increasing emissions from the coast inland: (1) the peat surfaces of the fens emit far less methane than the surfaces of the interior bogs; (2) the pools on the fens emit much more methane than the adjacent peat surfaces, and; (3) the fraction of open peatlands with a significant amount of surface water increases from the fen near the coast to the interior bogs.

It has been shown that fens generally emit more methane than bogs and this has been attributed to the higher net primary productivity (NPP) of fens [e.g., Aselmann and Crutzen, 1989] and greater surface wetness in fens [Glaser, 1987]. The pattern observed in this study is exactly opposite: the fens yield the least methane and the interior bogs the most. This results from differences in the production and oxidation of CH_4 among the various wetlands. The fen peat displayed the greatest potential for the production of CH_4 of any peat type along the transect [Moore et al., this issue] but the same peat also had a disproportionately higher potential for the oxidation of CH_4. The general pattern of CH_4 fluxes was confounded by the presence of pools on many of the peatlands. The flux of CH_4 from the pools is a function of the biogeochemical processes which occur in the pools themselves [Hamilton et al., this issue] and possible decomposition of peat from the sediments and sides of the pool [Moore et al., this issue]. The relative importance of the flux of CH_4 from the pools in the regional flux is not because the pools themselves are unusually large emitters, as the flux from pools is comparable to the flux from many peatlands [cf. Crill et al., 1988; Moore et al., 1990; Sebacher et al., 1986; Whalen and Reeburgh, 1988], but because the vegetated portions of the HBL peatlands are very low emitters compared to many other peatlands not in the HBL.

When the NOWES was originally conceived [1988], it was assumed that the HBL would emit ≈ 7 to 8 Tg CH_4 yr^{-1}, based on 10% of the flux for northern wetlands derived by Matthews and Fung [1987], as the HBL comprises ≈ 10% of all northern wetlands. Our estimate of 0.538 ± 0.187 Tg CH_4 yr^{-1} is about 15 times smaller. More recently, Aselmann and Crutzen [1989] and Fung et al. [1991] have reduced the northern wetland source to 22 and 35 Tg CH_4 yr^{-1}, repectively. Ten percent of these estimates is 2.2 and 3.5 Tg CH_4 yr^{-1}, which is still 4 to 6 times larger than our estimate. Using the highest flux estimate from the HBL based on the error analysis using the upper quartile (3.722 Tg CH_4 yr^{-1}), there is little difference between our estimate and the prorated estimates using Aselmann and Crutzen [1989] and Fung et al. [1991], but using the linear combination of errors (0.484 Tg CH_4 yr^{-1}) there is still a factor of 2 to 3 difference. However, when the potential sources of errors in the global budgets are also considered the differences reported above are small. If the Western Siberian lowland (WSL) has similar fluxes to the HBL, then the overall emissions from northern wetlands may be as low as 17 Tg CH_4 yr^{-1}. This is based on 2.4 x 10^6 km^2 of northern wetlands, using the Aselmann and Crutzen flux from northern wetlands not in the HBL and WSL, and assuming the HBL and WSL represent 30% of this area and that the HBL and WSL are ecologically similar. The latter assumption is not unreasonable since they both developed on glacial emergent coastlines, and they experience similar climates [Botch and Masing, 1983; Mortsch, 1990; Riley, 1982]. This would mean northern wetlands represent only 3 to 4% of the global CH_4 source. This study lends strong empirical evidence for the model estimates of Fung et al. (1991).

The lower estimate results from the very low fluxes measured during the NOWES experiment and not from differences in the areal extent of wetlands assumed in our extrapolation. It is possible that the very low fluxes could be a result from the enclosures yielding systematically low fluxes. However, the comparison of the flux data from the aircraft and fluxes extrapolated using remote sensing from enclosure and pond measurements compared to within a factor of 3.7 in the worst case of the northern survey area, and to within a factor of 2 over the entire HBL. During the NOWES there were also several periods where the CH_4 fluxes were measured simultaneously by enclosures, and tower and airborne eddy correlation systems over the Kinosheo Lake area (Edwards et al., this issue; Ritter et al., this issue). While a detailed three-way comparison has not yet been made because analysis of the "footprints" still has to be undertaken, preliminary results indicate that they all agree to within a factor of 2. Even if the enclosures underestimated the flux by the worst case factor of 3.7, the annual emission from the HBL would increase to only 1.3 Tg CH_4 yr^{-1}. This would have no effect on the conclusions. Likewise, the study period was wetter (≈ 20%) and warmer (≈ 2°C) than normal which would lead to higher not lower than normal fluxes. Whalen and Reeburgh [1992], in a 4-year times series, demonstrate a large within site and interannual variability in methane flux.

Their work [e.g. Bartlett et al., 1989; Moore et al., 1990] shows that the separation of the temporal from the spatial variance will require long-term measurements spanning 5 to 10 years using many enclosures at one location.

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