Tellus (1990), *42B*, 237–249

A methane flux transect along the trans-Alaska pipeline haul road

By S. C. WHALEN and W. S. REEBURGH, *Institute of Marine Science, University of Alaska, Fairbanks, Alaska 99775, USA*

(Manuscript submitted 9 May 1989; in final form 24 August 1989)

ABSTRACT

Methane flux measurements were made during the summer of 1987 at 10 km intervals along a north–south transect from Prudhoe Bay (70°13′N) to the Arctic Circle (66°30′N) in Alaska. A regional comparison showed that the mean CH_4 flux from arctic tundra (52 mg m^{-2} d^{-1}) was significantly greater than the mean from high latitude taiga (11 mg m^{-2} d^{-1}). Sites occupied on the transect were classified into 6 categories based on differences in plant communities and CH_4 emission was further compared. Mean CH_4 fluxes (mg m^{-2} d^{-1}) for each category were: wet tundra, 90; low brush-muskeg bog, 45; moist tundra, 31; freshwater ponds, 21; spruce forest, 4.6; and alpine tundra, 0.6. Differences among means were statistically significant. During the period of observation, CH_4 emission was only weakly correlated with soil temperature, water table depth, thaw depth and organic layer depth. Extending these fluxes to appropriate areas and emission periods yields independent estimates of annual CH_4 emission from global tundra and taiga environments of 38 Tg and 15 Tg. This is about 46% of the wetland emission term or 10% of the global atmospheric input.

1. Introduction

The recently documented concentration increase in atmospheric CH_4 (Khalil and Rasmussen, 1983; Rinsland et al., 1985; Steele et al., 1987; Blake and Rowland, 1988), a radiatively active gas that could be important in climatic change, has stimulated research on terms important in the global CH_4 budget. One of the most important terms is emission from natural wetlands (115 Tg CH_4 yr^{-1}, range 100 to 200; Cicerone and Oremland, 1988). The large uncertainty in the wetland release term results from several factors. First, there is high spatial variability in CH_4 emission within ecosystems on a scale of meters (Svensson and Rosswall, 1984) to kilometers (Harriss et al., 1985). Second, temporal (seasonal) variability in CH_4 flux within ecosystems is high, due to such factors as changing soil moisture and temperature (Crill et al., 1988). Third, estimates of the areal extent of wetland environments and their ecological characteristics require further refinement (Matthews and Fung, 1987).

The northern boreal forest (taiga) and arctic tundra are important areally and in the global soil carbon budget. Together, these regions cover 19.9×10^6 km^2 and store 27% of the earth's soil carbon (Billings, 1987). Over 50% of the earth's wetlands occur between 50° and 70°N (Matthews and Fung, 1987), which is roughly the area encompassed by the taiga and arctic tundra. However, the data base for CH_4 emission from high latitude taiga and arctic tundra is the poorest for all wetland regions. Flux determinations have been reported only by Svensson (1976), Svensson and Rosswall (1984) and Sebacher et al. (1986).

The work reported here is part of a study whose overall aim is to assess temporal and spatial variations in CH_4 flux and processes modulating CH_4 flux from high latitude environments. Our experimental design employs both time series and survey measurements to address temporal and spatial variability in CH_4 flux from these environments.

One component of this study examines in the University of Alaska Arboretum temporal

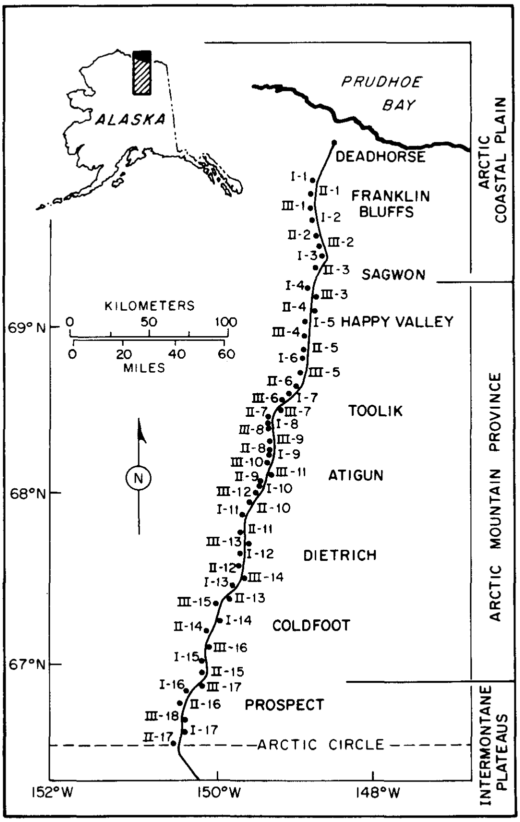


Fig. 1. Map of study area showing sampling site locations.

(~weekly) and spatial (sub-meter) variability of CH_4 flux and environmental variables in triplicate, permanent plots in discrete floristic units characteristic of tussock and wet meadow tundra (Whalen and Reeburgh, 1988). Additional data are being collected less frequently in similar, permanent sites in the Toolik and Deadhorse regions of the Alaskan arctic (Fig. 1). The first year's data from the arboretum sites and a recent areal estimate of these broadly defined tundra types (Matthews, 1983) were used to produce a preliminary estimate of the CH_4 source strength of the arctic tundra (Whalen and Reeburgh, 1988).

This report gives the results of a second component of the study. Here we extend our observations to include both arctic tundra and high latitude taiga by survey sampling along the route between our arctic and subarctic permanent plots. Sebacher et al. (1986) sampled less extensively along this same route in a CH_4 flux transect through northern and central Alaska. Our study differs from Sebacher et al. (1986) and many other investigations of wetland CH_4 emission (cf. Crill et al., 1988; Harriss et al., 1988) in that the odometer reading was used here to guide site selection as opposed to gradients in vegetation, topography or soil moisture. This sampling strategy was designed to address the general problems of large scale spatial variability in CH_4 flux and uncertainty in the areal extent of tundra and boreal wetlands.

The three goals of this study were to: (a) obtain estimates of annual CH_4 emission from arctic and boreal regions; (b) examine spatial variability in CH_4 emission on a regional and kilometer scale and (c) identify environmental factors influencing CH_4 flux. The first goal was accomplished by occupying a latitudinal transect along the Trans-Alaska Pipeline Haul Road from Prudhoe Bay on the Arctic Coastal Plain (70°13′N; 148°W) to the Arctic Circle (66°33′N; 151°W) in the Alaskan taiga. Samples were collected at 10 km intervals in a geographically systematic scheme to obtain a representative sample of environments. This approach avoids a "hotspot" bias (Henrichs and Reeburgh, 1987) and eliminates the need for an areal estimate of wetlands in the arctic tundra and taiga in calculating CH_4 source strengths for these regions. The second goal was met by evaluating CH_4 flux by region (arctic tundra or taiga) and by a further subdivision into six general plant associations, assuming that vegetative zonation was broadly related to morphoedaphic, physiographic and climatic controls on emission. The third goal was addressed by correlating data for a suite of environmental variables collected at each site with CH_4 flux measurements.

2. Experimental methods

Three transects were occupied along the Haul Road from Prudhoe Bay to the Arctic Circle in the summer of 1987 (Fig. 1). The Haul Road is a gravel roadway linking Prudhoe Bay oil fields to the Elliott Highway in interior Alaska. Mile post (MP) indicators appear at 1-mile (1.6 km) intervals along the entire length of the road from Livengood in the subarctic taiga (MP 1) to Deadhorse on the arctic coast (MP 416). The first site occupied on transect I (12–15 July) was at MP 412 (site I-1); successive sites were located at ~30 km increments until site I-17 was reached just north of the Arctic Circle (MP 115). Sites were generally located about 200 m normal to the west side of the road (beyond the obvious influence of construction disturbance and dust) near the appropriate MP marker. Transects II (4–10 August) and III (24–27 August) followed similar conventions except that the starting points were adjusted so that the composite transect contained data from 10 km intervals.

A static chamber technique was used to measure the net CH_4 flux across the air–soil interface at two locations separated by <5 m within each sample site. Chambers were fitted with styrofoam collars to measure flux across the air–water interface in standing water systems. Guidelines given by Mosier (1989) were followed in chamber design and deployment to ensure reproducibility and consistency in flux determinations. Syringe samples collected from each chamber over a 0.5 h time course were analyzed for CH_4 by flame ionization gas chromatography, and the net flux was computed from a least squares fit of concentration change versus time within the chamber. Details are given in Whalen and Reeburgh (1988).

The minimum detectable flux was ± 0.2 mg CH_4 m^{-2} d^{-1}; values within this range were considered to be no different from zero. A site was considered to be disturbed if the CH_4 concentration at time zero (initial sample, taken immediately after chamber lid emplacement) was elevated significantly (>2.0 ppmv) relative to the atmospheric level (1.7 ppmv). Data judged to be disturbed were eliminated.

Supporting data were collected at each site. The organic matter and water table depths were determined by excavating a shallow hole. A soil temperature profile was taken with a portable multi-thermistor (2 cm intervals to 15 cm) probe and the mean soil temperature was calculated as the average of these equally spaced measurements. The thaw depth was determined by inserting a 3 mm diameter brass rod to the freezing horizon. A qualitative plant census was taken. The detection limits for the thaw and organic matter depth were 75 and 30 cm (measured positively downward from the soil surface), while that for the water table depth was -30 cm (measured positively upward from the soil surface). The organic matter depth is reported only when a distinct break was found between the organic and inorganic horizons.

Statistical treatment of the data follows Koch and Link (1970) and Zar (1984). A significance level of $\alpha = 0.05$ was used for all tests.

3. Field study

3.1. General description

The study area spans several major climatic, physiographic and vegetative regions. Information from Brown and Berg (1980), Brown and Kreig (1983), Wahrhaftig (1965), University of Alaska (1975, 1976) and U.S. Department of the Interior (1987) was used to assemble the following description of the geomorphology, vegetation, soils and climate of the study area.

Along the transect, the taiga (northern coniferous forest) region occurs south of Atigun and the arctic tundra region (treeless area north of the latitudinal treeline) is found north of Atigun (Fig. 1). Terrain from Prospect to the base of the Brooks Range at Atigun generally consists of rolling uplands and east-trending ridges that gradually increase in elevation from 1400 to 2700 m. The area immediately north of Atigun grades from east-trending ridges and hills to undulating tundra uplands in the Toolik and Happy Valley areas. Sagwon marks the beginning of the Arctic Coastal Plain, which is characterized by low relief, poor drainage and oriented thaw ponds.

Vegetation from Prospect to Atigun (Fig. 1) consists of a black spruce (*Picea mariana*) forest with an undergrowth of mosses, grasses and shrubs at upland sites. Poorly drained areas exhibit a thinner and stunted spruce overstory with a subordinate mat of mosses and cottongrass tussocks (*Eriophorum vaginatum*). Shrubs, lichens and mosses replace forest vegetation at higher elevations. North of Atigun to Sagwon, nearly complete ground cover is provided by an *E. vaginatum* plant community. Vegetation of the Arctic Coastal Plain is primarily a mat of non-tussock sedges and mosses.

Permafrost is discontinuous in the Intermontaine Plateaus and continuous elsewhere in the study regions. The thaw depth is highly variable south of Atigun and 0.5 m or less to the north. Toward the north along the transect the mean annual temperature, thaw season and precipitation decrease from about −5°C, 145 d and 300 mm to −11°C, 110 d and 220 mm; the frozen fraction of annual precipitation increases from about 34 to 50%.

Soils south of Atigun often have a thick organic horizon with moderately well drained areas showing a fine textured upper horizon over gravelly subhorizons. Lower slopes and valley bottoms have a poorly decomposed organic layer of variable thickness overlying a poorly drained, gray mineral horizon. Soils north of Atigun are wet, shallow and sometimes weakly differentiated. Most of the organic matter is partly decomposed and peat accumulates in depressions.

3.2. Site classification

We have grouped sites into 6 working types, based on our photographs and descriptions of local topography and plant assemblages. The classification scheme roughly follows that given by University of Alaska (1975, 1976) for arctic tundra and boreal regions except where noted. A generalized description for each site type follows; a list of representative plant species for each site type is given in Appendix A.

Aquatic sites (AQU) include areas of permanent ponds and lakes beyond the reach of emergent vegetation.

Alpine tundra (ALP) occurs on mountainous areas, exposed ridges and rubble slopes in both the arctic tundra and taiga regions. The soil is coarse, rocky and dry. Plants generally show a low growth form. Characteristic plant associations are lacking, but mosses, lichens, dwarf shrubs and scattered grasses are found. Ground cover may be discontinuous.

Moist tundra (MST) is a mosaic of mosses and the cottongrass tussock, *E. vaginatum*. Tussocks are often invaded by other sedges and low shrubs. Frost action sometimes creates naked boils to interrupt the otherwise complete ground cover. High brush assemblages develop along stream margins. This plant community dominates the rolling tundra between Sagwon and Atigun, and occurs locally in the taiga region. The MST type is equivalent to the moist tundra and high brush communities in University of Alaska (1975, 1976).

Wet tundra (WET) is often found where soils are saturated throughout the thaw season. It is characteristic of the Arctic Coastal Plain, but occurs in the taiga as well. Non-tussock cottongrasses and other sedges with a cover of mosses form the dominant plant association; extensive stands of *Carex aquatalis* are common. Dwarf shrubs and herbaceous plants occur where microrelief extends above the water table.

The low brush-muskeg bog type (BOG) occurs on poorly drained depressions in the taiga too low for substantial tree growth. Vegetation consists of varying amounts of *E. vaginatum* and other sedges, *Sphagnum* sp. and other mosses, shrubs and stunted *P. mariana*, depending on soil moisture conditions. This site type is similar to the low brush-muskeg bog and lowland spruce associations in University of Alaska (1975, 1976).

The spruce forest (SPF) develops where moderate to well drained soils are capable of supporting extensive tree growth. The overstory is formed by *P. mariana* with a height of <5 m and a canopy coverage of 25 to 60%. The undergrowth is again moisture dependent, but is largely a mix of mosses, lichens, *E. vaginatum* and shrubs. This site type is equivalent to the bottomland spruce and upland spruce associations in University of Alaska (1975, 1976).

The site types described above best correspond to the international vegetation classification of UNESCO (1973) as follows: ALP, 143 IV.D.2 (mainly lichen tundra); BOG, 143 IV.E (mossy bog formations with dwarf shrub); MST, 209 V.C.8a (graminoid bunch-form tundra); SPF, 86 II.A.2c (evergreen needle-leaved woodland with very narrow cylindro-conical crowns); and WET, 211 V.C.8b(1) (graminoid sod-form tundra, seasonally flooded). There is no UNESCO vegetation type equivalent to the AQU type described here.

With the exception of AQU sites, sampling sites often exhibited vegetative and topographic heterogeneity on a scale of less than 1 m. We accounted for this patchiness in our within-site sampling strategy. For example, on moist tundra one chamber was deployed over a tussock and the other over moss or a frost boil.

4. Results and discussion

A total of 52 sites were occupied (Fig. 1; Appendix B). Moist (MST) and wet (WET) tundra accounted for 87% of the observations in the arctic (Fig. 2). Dominant taiga site types were SPF and BOG, with a combined relative frequency of 67%. The observed distributions of site types in both the arctic tundra and taiga regions were not significantly different (Log Likelihood Ratio) from the distributions reported in an independent, statewide survey of Alaskan vegetation (University of Alaska, 1975, 1976). Therefore, our experimental design yielded floristically representative samples of these regions.

A total of 104 CH_4 flux determinations were made, but six were eliminated from the data set. Two measurements were eliminated on site due to a poor seal at the air–soil interface, two showed disturbance during chamber emplacement and two were rejected statistically (Full Normal Plot) as outliers. The remaining 98 observations were lognormally distributed (Fig. 3).

Methane flux measurements ranged from -0.3 to 265 mg m^{-2} d^{-1} with an overall mean of 33 (Table 1). Within-site variability was high, as coefficients of variation for flux from duplicate chambers averaged 51%. Variability in CH_4 flux on a length scale of meters is not unusual and is certainly enhanced by our effort to incorporate the natural patchiness evident at each site in the sampling strategy. Methane emission on a given date ranged over more than two orders of magnitude both within and among discrete vegetative units in permanent muskeg plots (Whalen and Reeburgh, 1988). Crill et al. (1988; Fig. 5) show variability nearly as high for fluxes measured along 100 to 200 m transects in two Minnesota bogs.

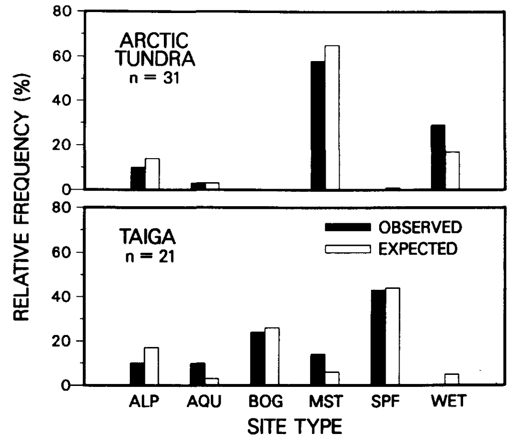


Fig. 2. Observed frequency distribution of site types in a composite latitudinal transect measuring methane flux from Alaskan arctic tundra and taiga environments versus the expected frequency distribution based on vegetation surveys by University of Alaska (1975, 1976).

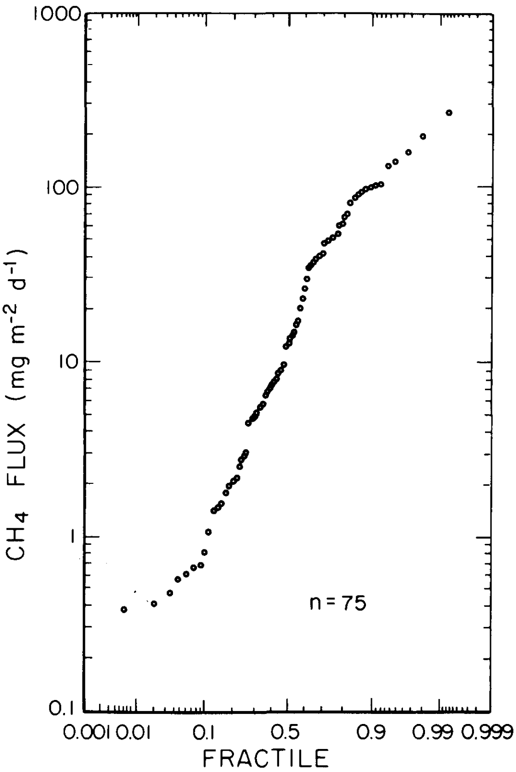


Fig. 3. Probability distribution function for net positive ($n = 75$) methane fluxes observed in a composite latitudinal transect in Alaskan arctic tundra and taiga. Entire data transformed as log(flux + 1) to include net negative ($n = 3$) and zero ($n = 20$) fluxes showed a similar distribution.

When grouped by site type, CH_4 fluxes remained lognormally distributed. The data showed means ranging from 0.6 (ALP) to 90 (WET) mg CH_4 m^{-2} d^{-1} (Table 1). Differences among means were statistically significant (Kruskal-Wallis One-Way ANOVA). Analysis of the differences (Dunn's nonparametric multiple com-

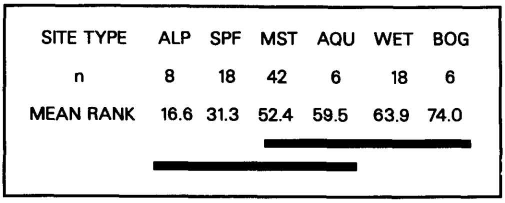
Table 1. *Summary statistics by site type for methane flux measurements (mg CH_4 m^{-2} d^{-1}) made along a composite latitudinal transect in Alaskan arctic tundra and taiga; site types are classified by vegetation assemblages: ALP, alpine tundra; AQU, aquatic; BOG, low brush-muskeg bog, MST, moist tundra; SPF, spruce forest; and WET, wet tundra*

	Site type						
Statistic	ALP	AQU	BOG	MST	SPF	WET	All data
n	8	6	6	42	18	18	98
minimum	−0.2	4.6	12	0.0	−0.3	0.0	−0.3
maximum	6.3	131	101	159	67	265	265
median	0.0	8.4	36	7.6	0.5	42	6.0
mean	0.6	21	45	31	4.6	90	33
95% CI*	<0–1.9	6–75	18–113	19–52	1.9–9.8	35–230	23–47

* 95% confidence interval about the mean.

parison procedure) gave somewhat ambiguous results (Fig. 4). Fluxes from WET and BOG sites were clearly greater than from ALP and SPF sites, but the test was unable to identify from which population MST and AQU sites came. A larger data set would result in increased power. These results are encouraging, however, as they indicate that roughly grouped plant assemblages show potential for use as predictors of CH_4 flux.

Differences in sites sampled and in chamber footprint relative to topographic and vegetative patchiness within a site type permit only generalized comparisons (Whalen and Reeburgh, 1988). Geographically, the only direct comparison is with data from Sebacher et al. (1986) collected along the Haul Road and interior Alaskan highways. Our WET sites are floristically equivalent to their coastal tundra and mean CH_4 emissions were similar at 90 (Table 1) and 119 mg m^{-2} d^{-1}.



SITE TYPE	ALP	SPF	MST	AQU	WET	BOG
n	8	18	42	6	18	6
MEAN RANK	16.6	31.3	52.4	59.5	63.9	74.0

Fig. 4. Multiple comparison of ranked methane fluxes in Alaskan arctic tundra and taiga by Dunn's nonparametric procedure. Mean ranks for six site types were arranged in increasing order. Those not underscored by the same line show significantly different methane fluxes; those underscored by the same line have fluxes that are not significantly different.

Their boreal marsh site shows a CH_4 flux (106 mg m^{-2} d^{-1}) that is 2.5 times greater than the mean for BOG, but still falls within the 95% confidence interval. Means for Brooks Range moist (4.9 mg CH_4 m^{-2} d^{-1}) and wet meadow tundra (39) bracket that for the equivalent site type, MST. Whalen and Reeburgh (1988) reported average summer CH_4 emission rates of 22 and 25 mg m^{-2} d^{-1} for subarctic equivalents of MST and WET sites, roughly 71 and 28% of the values found here. Moore and Knowles (1987) gave rates of a similar magnitude for a subarctic Canadian fen, 19 to 46 mg CH_4 m^{-2} d^{-1}. Svensson and Rosswall (1984) measured fluxes ranging from 0.3 to 191 mg CH_4 m^{-2} d^{-1} for a mire at 68° N, but no overall mean was given.

Methane fluxes from more southern peatlands are about an order of magnitude higher than the overall mean here. Harriss et al. (1985) reported a mean emission rate of 337 mg CH_4 m^{-2} d^{-1} for survey samples from Minnesota peatlands while Crill et al. (1988) gave an average of 207 mg m^{-2} d^{-1} for sites in the same locale visited repeatedly throughout the summer.

Net CH_4 consumption (a decrease in chamber concentration with time) was observed in three deployments, two in ALP and one in SPF sites. This has also been reported for the MST variant (King et al., 1988) and for temperate (Keller et al., 1983; Harriss et al., 1982; Born et al., 1990), tropical (Keller et al., 1986) and subtropical (Seiler et al., 1984) soils. Net consumption rates in all of these environments fall roughly within the range −0.2 to −1.5 mg m^{-2} d^{-1}. Born et al.

Table 2. *Summary statistics for environmental variables measured along a composite latitudinal transect in Alaskan arctic tundra and taiga; number of observations exceeding detection limits given in parentheses*

	Variable			
Statistic	Soil temperature (°C)	Organic layer depth (cm)	Water table depth (cm)	Thaw depth (cm)
n	53	52	54	53
minimum	0.9	1	<-30 (11)	8
maximum	17.9	>30 (18)	25	>75 (8)
median	7.1	24	-7	44

(1990) have calculated that the annual global destruction of atmospheric CH_4 by aerated soils may amount to 1 to 15% of the destruction by the OH radical. Atmospheric CH_4 consumption by tundra deserves increased study because of its areal extent (7.34×10^6 km^2; Matthews, 1983) and the omission of tundra in the calculation of Born et al. (1990).

Table 2 shows the range of values for the four variables measured in conjunction with flux determinations. The data are highly variable and are pooled because comparison by site type or region showed no apparent differences. The ranges for the environmental variables measured here are in agreement with those reported by Sebacher et al. (1986) for the Alaskan arctic and taiga.

Although correlations were made on ranked data, methane emission was only weakly linked to environmental variables (Table 3). Pooling the entire data set or analysis by region or site type did little to improve correlations. All significant correlations for samples of size $n > 4$ were positive, as expected.

Other investigators have reported a strong linear (Svensson and Rosswall, 1984), curvilinear (second order polynomial; Baker-Blocker et al., 1977) or log-linear (Holzapfel-Pschorn and Seiler, 1986; Crill et al., 1988) relationship between CH_4 emission and soil or air temperature for wetlands. In addition, CH_4 fluxes have been logarithmically related to water levels (Sebacher et al., 1986) and moisture content (Svensson, 1976). In many instances, these relationships were estab-

Table 3. *Spearman's rank correlation coefficients (r_s) for correlations between methane flux from Alaskan arctic tundra and taiga and environmental variables*

	r_s			
Region or site type	Organic layer depth	Water table depth	Thaw depth	Mean soil temperature
ALP		ND		
AQU	ND		-0.89 (4)	0.84 (6)
BOG	-0.89 (4)		ND	
MST	0.45 (30)			0.44 (42)
SPF		0.66 (14)	0.54 (14)	
WET				
arctic tundra	0.58 (36)	0.44 (46)		
taiga		0.56 (30)	0.51 (22)	0.36 (36)
all data	0.33 (65)	0.45 (76)	0.31 (82)	0.34 (98)

Only statistically significant values of r_s are shown; the number of observations (n) is given in parentheses. ND = no data ($n < 2$). Site types are abbreviated as follows: ALP, alpine tundra; AQU, aquatic; BOG, low brush-muskeg bog; MST, moist tundra; SPF, spruce forest; WET, wet tundra.

lished by repeated occupation of the same site over an entire season, so that many other physicochemical variables were held reasonably constant. The more general case for opportunistic sampling (present investigation) is that the supporting information collected in conjunction with flux determinations affords little predictive power. The response of CH_4 flux to a single, easily measured environmental variable is probably obscured by interactions among factors such as spatial differences in organic matter quality, bacterial activity, soil porosity, chemistry and permeability, vegetative cover, drainage and topography.

Mean CH_4 fluxes (with 95% confidence interval, CI) from arctic tundra ($n = 62$) and taiga ($n = 36$) regions were 52 (33–82) and 11 (7–19) mg m^{-2} d^{-1}, respectively. The difference was statistically significant (Mann-Whitney *U*-test), indicating that the average CH_4 flux was greater for the arctic tundra than the taiga.

Because the sampling site distribution satisfactorily represents the existing vegetation distribution, mean regional fluxes are appropriately weighted to estimate CH_4 emission from arctic tundra and taiga regions in Alaska. Assuming that the relative frequency of site types in Alaska is representative of the arctic tundra and taiga worldwide, the global source strength for each region is simply the product of its areal extent, the mean daily flux and the duration of the period of emission. Considering the arctic tundra to occupy 7.34×10^6 km^2 (Matthews, 1983) and an active season of 100 d, the annual CH_4 flux (with 95% CI) is 38 (24–60) Tg. Similarly, using a global coverage of 11.1×10^6 km^2 (Billings, 1987) and a 120 d productive period, 15 (9–25) Tg CH_4 are emitted annually from the taiga. Emission from both regions is about 53 Tg yr^{-1}, which is 46% of the annual estimate of Cicerone and Oremland (1988) for all natural wetlands and 10% of the total released globally from all sources.

The annual arctic tundra emission of 38 Tg CH_4 given here is somewhat higher than previous estimates. Svensson (1976) and Whalen and Reeburgh (1988) give estimates of 0.6 to 24.9 and 19.3 to 32.7 Tg CH_4 yr^{-1}. The range of daily CH_4 fluxes and assumed areal extent of the arctic tundra are roughly similar in all studies. Differences are due to assumptions made in subdividing the arctic tundra to properly weight fluxes. Svensson (1976) focused on the relationship between soil moisture and CH_4 flux. The wide range of his estimate derives from assumed extremes in soil moisture content, owing to a lack of resolution in data for soil inundation. Whalen and Reeburgh (1988) divided arctic tundra into two vegetative regions for weighting annual time series data from a subarctic muskeg in their global estimate of the CH_4 source strength estimate for arctic tundra. The present study addresses the weighting problem by systematic sampling, but sacrifices the temporal resolution provided by the time series.

This estimate of 53 Tg CH_4 yr^{-1} for the source strength of the arctic and taiga regions (roughly the area poleward of 45° N; Kimmens and Wein, 1986) is on the low end of previous estimates for northern wetlands. Sebacher et al. (1986) calculated an annual CH_4 emission of 45 to 106 Tg from all arctic and boreal wetlands. Matthews and Fung (1987) give an estimated flux of 62 Tg CH_4 yr^{-1} for forested and non-forested bogs between 50° and 70° N while Crill et al. (1988) calculated an annual emission of 72 Tg from undrained peatlands above 40° N.

Although these estimates appear to be reasonably consistent, closer examination reveals two striking differences among studies. First, the BOG type here shows a four to five-fold lower mean flux than the data used by Matthews and Fung (1987) and Crill et al. (1988) in their source strength estimates. Second, the MST site type contributes substantially to the estimate given here (Table 1; Fig. 2), but is not considered by Matthews and Fung (1987) and Crill et al. (1988). These two studies base source strength estimates on mean fluxes from refined data for inundated areas while the present investigation uses a weighted mean flux from systematic sampling and the total areal coverage. The net effect is that MST emission compensates for the lower BOG flux so that all studies appear to be in agreement. The disparity becomes evident in a regional comparison with Matthews and Fung (1987). Their total source strength estimate of 62 Tg CH_4 yr^{-1} includes 42 Tg for forested bogs (roughly equivalent to taiga) and 20 Tg from non-forested bogs (arctic tundra). The estimated flux of 53 Tg CH_4 yr^{-1} in this investigation reverses the roles of the taiga and arctic tundra from the previous estimate; 15 Tg were emitted from the taiga and 38 from arctic tundra.

There are three possible explanations for our low mean flux from BOG sites. First, the sample size ($n = 6$) may have been inadequate to obtain a representative sample of this site type. Second, our estimate for this type comes exclusively from samples collected at the northern reaches of the taiga and may not account for latitudinal variations. The estimate of Crill et al. (1988) is based on intensive sampling of sites at 47°N while that of Matthews and Fung (1987) relies upon literature data for lower latitude bogs. Third, the low mean for the BOG variant may simply reflect interannual variability in modulators of flux. The second year of our time series for CH_4 flux from a subarctic muskeg shows roughly twice the precipitation and emission of the previous year (Whalen and Reeburgh, unpublished). This clearly demonstrates that there is considerable room for refinement of the estimate of global CH_4 emission from northern ecosystems.

5. Conclusions

The systematic sampling design used here yielded a representative sample of CH_4 fluxes from arctic tundra and high latitude taiga. The sample size ($n = 98$) was relatively small, so more intensive sampling is recommended to better estimate the global source strength of these regions. Two key areas are identified for future research: First, CH_4 flux surveys should focus on forested bogs between 50° and 65°N to identify latitudinal variations. Second, the role of unsaturated high latitude soils in both consumption and production of atmospheric CH_4 should receive increased attention.

This investigation was a first attempt at defining the gross spatial variability of CH_4 emission in the arctic and high latitude taiga, based on plant associations. Future studies should continue to address this issue on an even finer scale, but should also focus on the temporal component (seasonal and annual variability) and physicochemical and biological modulators of flux. These latter subjects are best addressed with time series measurements of flux and selected variables at permanently established plots in both regions.

6. Acknowledgements

This research was supported by NASA grant NASW 841, RTOP 147-92-41-01 to W. S. Reeburgh. D. L. Witt assisted in sampling and provided logistic support through the University of Alaska's field facility at Toolik Lake. D. B. Hawkins provided statistical advice. K. Kielland, K. Holmes and scientific personnel at the Toolik Lake camp assisted in plant identification. K. Kielland, K. Van Cleve and F. S. Chapin III commented on early drafts of the manuscript. Contribution 739 from the Institute of Marine Science, University of Alaska, Fairbanks.

7. Appendix A

Common plant species for site types in a composite latitudinal transect in Alaskan arctic tundra and taiga

Group	Common name	Scientific name
	Alpine tundra (ALP)	
Shrubs	Four-angled heather	*Cassiope tetragona*
	Crowberry	*Empetrum nigrum*
	Birches	*Betula* spp.
	Blueberry	*Vaccinium uliginosum*
	Lingonberry	*V. vitis-idaea*
	Laborador tea	*Ledum palustre*
	Bearberry	*Arctostaphylos* spp.

Herbs	Avens	*Dryas* spp.
	Oxytropes	*Oxytropis* spp.
	Bearflower	*Boykinia richardsonii*
Grasses/sedges	Sedges	*Carex* spp.
	Unidentified grasses	
Other*	Mosses	
	Lichens	
	Low brush-Muskeg bog (BOG)	
Shrubs/trees	Black spruce	*Picea mariana*
	Birches	*Betula* spp.
	Willows	*Salix* spp.
	Laborador tea	*Ledum palustre*
	Blueberry	*Vaccinium uliginosum*
	Lingonberry	*V. vitis-idaea*
	Bog rosemary	*Andromeda polifolia*
	Soapberry	*Shepherdia canadensis*
	Bearberry	*Arctostaphylos* spp.
	Cloudberry	*Rubus chamaemorus*
Grasses/sedges	Cottongrass tussock	*Eriophorum vaginatum*
	Cottongrasses	*Eriophorum* spp.
	Sedges	*Carex* spp.
Other*	Mosses	
	Moist tundra (MST)	
Shrubs	Willows	*Salix* spp.
	Birches	*Betula* spp.
	Blueberry	*Vaccinium uliginosum*
	Lingonberry	*V. vitis-idaea*
	Laborador tea	*Ledum palustre*
	Cloudberry	*Rubus chamaemorus*
	Azalea	*Loiseleuria procumbens*
	Crowberry	*Empetrum nigrum*
	Bearberry	*Arctostaphylos rubra*
	Lapland rosebay	*Rhododendron lapponicum*
	Four-angled heather	*Cassiope tetragona*
Herbs	Avens	*Dryas* spp.
	Bistort	*Polygonum* spp.
	Bog rosemary	*Andromeda polifolia*
	Cinquefoil	*Potentilla fruticosa*
	Saxifrages	*Saxifrage* spp.
Grasses/sedges	Cottongrass tussock	*Eriophorum vaginatum*
	Cottongrasses	*Eriophorum* spp.
	Sedges	*Carex* spp.
Other*	Horsetails	*Equisetum* spp.
	Mosses	
	Lichens	
	Wet tundra (WET)	
Shrubs	Willows	*Salix* spp.
	Birches	*Betula* spp.

Herbs	Saxifrages	*Saxifrage* spp.
	Louseworts	*Pedicularis* spp.
	Avens	*Dryas* spp.
Grasses/sedges	Cottongrasses	*Eriophorum* spp.
	Sedges	*Carex* spp.
Other*	Mosses	
	Spruce forest (SPF)	
Shrubs/trees	Black spruce	*Picea mariana*
	Birches	*Betula* spp.
	Willows	*Salix* spp.
	Laborador tea	*Ledum palustre*
	Lingonberry	*Vaccinium vitis-idaea*
	Blueberry	*V. uliginosum*
	Bearberry	*Arctostaphylos* spp.
	Soapberry	*Shepherdia canadensis*
	Cloudberry	*Rubus chamaemorus*
	Crowberry	*Empetrum nigrum*
	Alders	*Alnus* spp.
	Four-angled heather	*Cassiope tetragona*
Herbs	Avens	*Dryas* spp.
	Wintergreen	*Pyrola* spp.
Grasses/sedges	Cottongrass tussock	*Eriophorum vaginatum*
	Cottongrasses	*Eriophorum* spp.
	Sedges	*Carex* spp.
Other*	Horsetails	*Equisetum* spp.
	Mosses	
	Lichens	

---

* Genera of mosses and lichens commonly encountered along composite transect

Mosses	Lichens
Sphagnum	*Cladonia*
Aulacomnium	*Cetraria*
Hylocomium	*Stereocaulon*
Tomenthypnum	*Pertusaria*
Dicranum	*Thamnolia*
Drepanocladus	*Alectoria*
Polytrichum	*Asahinea*
	Cornicularia
	Dactylina
	Peltigera

8. Appendix B

Location and vegetative classification of sites sampled in a composite latitudinal transect measuring CH_4 flux in Alaskan arctic and taiga. Letter adjacent to approximate milepost (MP) marker indicates whether west (W) or east (E) side of road was sampled

Transect I			Transect II			Transect III		
Site	MP	Type	Site	MP	Type	Site	MP	Type
1	412W	WET	1	407W	WET	1	400W	WET
2	394W	WET	2	387W	WET	2	382W	WET
3	377W	WET	3	368W	MST	3	354E	MST
4	360W	WET	4	348W	AQU	4	336W	MST
5	343W	WET	5	329W	MST	5	318W	MST
6	325W	MST	6	311W	MST	6	302W	ALP
7	308W	MST	7	291W	MST	7	296E	MST
8	290W	MST	8	273W	MST	8	284W	MST
9	272W	MST	9	254W	ALP	9	279W	MST
10	253W	MST	10	242W	MST	10	266W	MST
11	234W	MST	11	227W	SPF	11	260E	MST
12	216W	SPF	12	210W	BOG	12	249W	ALP
13	199W	MST	13	193W	AQU	13	221E	SPF
14	182E	SPF	14	176W	SPF	14	204E	SPF
15	163W	BOG	15	157W	SPF	15	188W	SPF
16	145W	BOG	16	139W	BOG	16	169E	SPF
17	126E	BOG	17	120W	ALP	17	151E	AQU
						18	132E	ALP

REFERENCES

Baker-Blocker, A., Donahue, T. M. and Mancy, K. H. 1977. Methane flux from wetland areas. *Tellus 29*, 245–250.

Billings, W. D. 1987. Carbon balance of Alaskan tundra and taiga ecosystems: past, present and future. *Quat. Sci. Rev. 6*, 165–177.

Blake, D. R. and Rowland, F. S. 1988. Continuing worldwide increase in tropospheric methane. *Science 239*, 1129–1131.

Born, M., Dörr, H. and Levin, I. 1990. Methane concentration in aerated soils in West-Germany. *Tellus 42B*, 58–64.

Brown, J. and Berg, R. L. 1980. *Environmental engineering and ecological baseline investigations along the Yukon River-Prudhoe Bay Haul Road.* Cold Regions Res. Eng. Lab. Rept. 80-19, Hanover, New Hampshire, 187 pp.

Brown, J. and Kreig, R. A. 1983. *Guidebook to permafrost and related features along the Elliott and Dalton Highways, Fox to Prudhoe Bay, Alaska (Guidebook 4).* Anchorage/Alaska: Alaska Division of Geological and Geophysical Surveys, 230 pp.

Cicerone, R. J. and Oremland, R. S. 1988. Biogeochemical aspects of atmospheric methane. *Global Biogeochem. Cycles 2*, 299–327.

Crill, P. M., Bartlett, K. B., Harriss, R. C., Gorham, E., Verry, E. S., Sebacher, D. I., Madzar, L. and Sanner, W. 1988. Methane flux from Minnesota peatlands. *Global Biogeochem. Cycles 2*, 371–384.

Dickinson, R. E. and Cicerone, R. J. 1986. Future global warming from atmospheric trace gases. *Nature 319*, 109–115.

Harriss, R. C., Sebacher, D. I. and Day, F. P. 1982. Methane flux in the Great Dismal Swamp. *Nature 297*, 673–674.

Harriss, R. C., Gorham, E., Sebacher, D. I., Bartlett, K. B. and Flebbe, P. A. 1985. Methane flux from northern peatlands. *Nature 315*, 652–654.

Harriss, R. C., Sebacher, D. I., Bartlett, K. B., Bartlett, D. S. and Crill, P. M. 1988. Sources of atmospheric methane in the South Florida environment. *Global Biogeochem. Cycles 2*, 231–243.

Henrichs, S. M. and Reeburgh, W. S. 1987. Anaerobic mineralization of marine sediment organic matter:

Rates and the role of anaerobic processes in the oceanic carbon economy. *Geomicrobiol. J. 5*, 191–237.

Holzapfel-Pschorn, A. and Seiler, W. 1986. Methane emission during a cultivation period from an Italian rice paddy. *J. Geophys. Res. 91D*, 11803–11814.

Keller, M., Goreau, T. J., Wofsy, S. C., Kaplan, W. A. and McElroy, M. B. 1983. Production of nitrous oxide and consumption of methane by forest soils. *Geophys. Res. Lett. 10*, 1156–1159.

Keller, M., Kaplan, W. A. and Wofsy, S. C. 1986. Emission of N_2O, CH_4 and CO_2 from tropical forest soils. *J. Geophys. Res. 91D*, 11791–11802.

Khalil, M. A. K. and Rasmussen, R. A. 1983. Sources, sinks and seasonal cycles of atmospheric methane. *J. Geophys. Res. 88C*, 5131–5144.

Kimmens, J. P. and Wein, R. W. 1986. Nature of taiga environment. Introduction. In *Forest ecosystems in the Alaskan taiga* (eds. K. Van Cleve, F. S. Chapin III, P. W. Flanagan, L. A. Viereck and C. T. Dyrness). New York: Springer-Verlag, 3–8.

King, S. L., Quay, P. D. and Lansdown, J. M. 1988. $^{13}C/^{12}C$ kinetic isotope effect for soil oxidation of methane at ambient concentrations. *EOS, Trans. Am. Geophys. Union 69*, 1084.

Koch, G. S. and Link, R. F. 1970. *Statistical analysis of geological data, Vol. 1.* New York: John Wiley and Sons, 375 pp.

Matthews, E. 1983. Global vegetation and land use: New high resolution data bases for climate studies. *J. Climate Appl. Meteorol. 22*, 474–487.

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

Moore, T. R. and Knowles, R. 1987. Methane and carbon dioxide evolution from subarctic fens. *Can. J. Soil Sci. 61*, 77–81.

Mosier, A. R. 1989. Gas flux measurement techniques with special reference to techniques suitable for measurements over large ecologically uniform areas. In *Proceedings of the International Conference on Soils and the Greenhouse Effect* (ed. L. Bouwman). New York: J. Wiley and Sons (In press).

Rinsland, C. P., Levine, J. S. and Miles, T. 1985. Concentration of methane in the troposphere deduced from 1951 infrared solar spectra. *Nature 318*, 245–249.

Sebacher, D. I., Harriss, R. C., Bartlett, K. B., Sebacher, S. M. and Grice, S. S. 1986. Atmospheric methane sources: Alaskan tundra bogs, an alpine fen and a subarctic boreal marsh. *Tellus 38B*, 1–10.

Seiler, W., Conrad, R. and Scharffe, D. 1984. Field studies of methane emission from termite nests into the atmosphere and measurement of methane uptake by tropical soils. *Atmos. Chem. 1*, 171–186.

Steele, L. P., Fraser, P. J., Rasmussen, R. A., Khalil, M. A. K., Conway, T. J., Crawford, A. J., Gammon, R. H., Masarie, K. A. and Thoning, K. W. 1987. The global distribution of methane in the troposphere. *J. Atmos. Chem. 5*, 125–171.

Svensson, B. H. 1976. Methane production in tundra peat. In *Microbial production and utilization of gases* (H_2, CH_4, *CO*) (eds. H. G. Schlegel, G. Gottschalk and N. Pfennig). Göttingen: E. Goltze KG, 135–139.

Svensson, B. H. and Rosswall, T. 1984. In situ methane production from acid peat communities with different moisture regimes. *Oikos 43*, 341–350.

United States Department of the Interior. 1987. *Utility corridor: Draft resource management plan and environmental impact statement.* Bur. Land Managment Rept. BLM-AK-PF87-016-1610-960.

UNESCO. 1973. *International classification and mapping of vegetation.* Paris: UNESCO, 93 pp.

University of Alaska, Arctic Environmental Information and Data Center. 1975. *Alaska regional profiles: Arctic region.* Salt Lake City/Utah: Wheelwright Lithographing Co., 218 pp.

University of Alaska, Arctic Environmental Information and Data Center. 1976. *Alaska regional profiles: Yukon region.* Salt Lake City/Utah: Wheelwright Lithographing Co. 346 pp.

Wahrhaftig, C. 1965. *Physiographic divisions of Alaska.* US Geol. Survey Prof. Pap. 482. Washington, D.C.: U.S. Government Printing Office, 52 pp.

Whalen, S. C. and Reeburgh, W. S. 1988. A methane flux time series for tundra environments. *Global Biogeochem. Cycles 2*, 399–409.

Zar, J. H. 1984. *Biostatistical analysis,* Second edn. Englewood Cliffs/New Jersey: Prentice-Hall, 718 pp.