# TERRESTRIAL BIOSPHERE-ATMOSPHERE EXCHANGE IN HIGH LATITUDES

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## ABSTRACT

This paper summarizes $CH_4$ flux measurements from high latitude tundra and wetland environments obtained during large field campaigns and a number of smaller local projects since 1986. Area-weighted time series $CH_4$ flux measurements at fixed sites in high latitude tundra and wetland environments suggest a $CH_4$ source strength of about 35 Tg $yr^{-1}$, which agrees reasonably with atmospheric model calculations. Individual flux measurements are subject to high spatial and temporal (daily to interannual) variability, and are strongly influenced by vegetation, soil temperature, thaw depth, and water table level, which influence the balance between $CH_4$ production and consumption. Field studies show that these subsurface parameters and $CH_4$ fluxes are often poorly correlated. Laboratory studies on varying water table level in tundra soil columns have shown long lag times and hysteresis in the fluxes under falling and rising water table conditions. These results indicate that the soil parameters are not independent variables and that a single parameter capable of predicting $CH_4$ flux is unlikely.

Boreal forest ecosystems appear to be a small net sink for $CH_4$. Microbially mediated oxidation of atmospheric $CH_4$ is the dominant process; wet bogs, fens, swamps, and beaver ponds are the only $CH_4$ sources. Microbial $CH_4$ oxidation is also an important modulator of tundra emission and has the potential to eliminate net $CH_4$ emission under warmer, drier conditions.

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Studies to date have emphasized $CH_4$, but future integrated studies along boreal forest and tundra transects will include measurements of other gases and carbon dioxide fluxes for estimates of carbon fixation and storage. Field manipulation experiments aimed at determining the sensitivity of high latitude trace gas emissions to temperature and moisture variations are also planned. High latitude biosphere-atmosphere studies to date have a strong North American bias. Collaborative studies in northern European and Siberian wetlands are essential to understanding the importance of high latitude ecosystems in trace gas budgets.

## INTRODUCTION

Two circumpolar components of Arctic and sub-Arctic ecosystems, tundra and boreal forest, have accumulated and stored soil carbon since the last glaciation. Tundra (area: $7.3 \times 10^{12}$ m$^2$; 7% of earth's land area) is the treeless Arctic and sub-Arctic plain populated with dwarf shrubs, graminoids and cryptogams, and is often underlain by permafrost. Tundra contains 13% of the earth's stored soil carbon. Boreal forest ($11.1 \times 10^{12}$ m$^2$) is a general term describing the mixed deciduous-coniferous forest biome located between the tundra and temperate forest or prairie. It contains about 14% of the stored soil carbon (Post *et al.*, 1982). Boreal wetlands (area: $1.5 \times 10^{12}$ m$^2$) occupy regions between 45° and 60°N, and are counted as part of tundra under most vegetation classification schemes. Approximately 30% of all northern wetlands are contained in two continuous wetland complexes: the Hudson Bay Lowland in Canada ($3.2 \times 10^{10}$ m$^2$) and the Vasuugan peatland ($5.4 \times 10^{10}$ m$^2$) in Siberia. All of these systems are characterized by short (100 to 120 day) growing seasons, low temperatures, low decomposition rates, moist to waterlogged soils, and the presence of continuous or discontinuous permafrost.

Much of the stored soil carbon in high latitude systems is present as peat or frozen in permafrost, and is subject to limited biogeochemical degradation. The fate of this stored carbon under altered climate is a major question (Billings, 1987). Model projections (Mitchell, 1989) indicate that Arctic regions will be the first impacted by global warming. Permafrost temperature distributions (Lachenbruch and Marshall, 1986) are consistent with a decade-scale rise in temperature. We understand in broad terms that $CH_4$ emissions result from a balance between production (methanogenesis) and consumption (methylotrophy), and that this balance is governed by temperature, moisture/water table relations, and substrate quality, but which variables are the best predictors of methane flux, the importance of feedbacks, and generally, the role of tundra under altered climate remains unclear. Some projections (Khalil and Rasmussen, 1989; Lashoff, 1989; Oechel *et al.*, 1993) suggest that warmer climate will lead to warmer soil temperatures, thawing permafrost and increased $CH_4$ and $CO_2$ emission. Others (Whalen and Reeburgh, 1990a; Reeburgh *et al.*, 1993; Moore and Roulet, 1993; Roulet *et al.*, 1993) suggest that microbially mediated $CH_4$ oxidation, which is neglected in the above projections, has the potential to modulate $CH_4$ emission, and under appropriate conditions, consume atmospheric $CH_4$.

This paper is structured around progress on the tasks of the IGAC High Latitude Ecosystems as Sources and Sinks for Trace Gases (HESS) Activity, which include:

Estimating the magnitude of high latitude ecosystem trace gas emissions.

Understanding factors and processes controlling high latitude ecosystem gas exchange.

Understanding sensitivity of high latitude trace gas sources and sinks to climate change.

Since these tasks are sequential, this paper will emphasize recent work on trace gas emissions from high latitude ecosystems and our current understanding of the role of high latitude environments in the $CH_4$ budget (Task 1), spell out our present understanding of the important controls on $CH_4$ fluxes (Task 2), and finally, outline manipulation experiments planned to determine sensitivity of high latitude systems to climate change (Task 3).

## ROLE OF HIGH LATITUDE ENVIRONMENTS IN THE GLOBAL METHANE BUDGET (Task 1)

### Early Studies

The possible importance of high latitude environments in radiatively active trace gas budgets was recognized early, but prior to 1986 only three studies provided information on $CH_4$ fluxes from high latitude systems (Clymo and Reddaway, 1971; Svensson and Rosswall, 1984a, b; Sebacher *et al.*, 1986). High latitude wetlands have been prominent as a potentially large term in the global $CH_4$ budget (Cicerone and Oremland, 1988; Matthews and Fung, 1987; Fung *et al.*, 1991), but their contribution has been uncertain because of three problem areas: lack of basic flux data, lack of understanding of the processes controlling fluxes, and uncertainties in scaling up from sites to regional and global scales. Large-scale coordinated field campaigns and individual projects have led to rapid growth in the high latitude $CH_4$ flux data base. The wetland $CH_4$ flux work has been summarized and reviewed recently by Bartlett and Harriss (1993). Because of the almost total absence of $CH_4$ flux data, net $CH_4$ fluxes have received major emphasis, but measurements of other gas fluxes are being incorporated in current work.

### Large Field Campaigns

**ABLE 3A.** The Arctic Boundary Layer Expedition (ABLE 3A) was conducted in the Arctic and sub-Arctic of North America during July and August of 1988. Studies included a comprehensive tower, chamber and aircraft campaign at a site in the Yukon-Kuskokwim Delta near Bethel, Alaska, and flights around Barrow, Alaska. A summary of the results appears in a dedicated 1992 issue (number D15) of the *Journal of Geophysical Research*; the following discussion will emphasize the $CH_4$ studies.

Methane flux measurements were made with methods covering three scales; aircraft boundary layer measurements (1000 km), tower measurements (103 m) and chamber measurements (1 $m^2$). Errors of approximately a factor of 2 between chamber and tower flux measurements resulted from poor resolution of $CH_4$ producing habitats in the tower footprint (Fan *et al.*, 1992). Mean aircraft fluxes were ~2 times higher than the tower fluxes. The aircraft data were obtained during afternoon in periods of good flying weather, and these conditions were associated with maximum tower fluxes. The tower and ground-based measurements were made in an area with small lakes, whose $CH_4$ flux varied with size and wind speed. A mean emission rate of 25 mg $CH_4$ $m^{-2}$ $d^{-1}$ for wet tundra, dry tundra and lakes, which is low compared to other sites, was made by areal weighting of vegetation types obtained from satellite imagery. Bartlett *et al.* (1992) extended this flux to a global emission rate for tundra of 11±3 Tg $CH_4$ $yr^{-1}$. Ritter *et al.* (1992) measured $CH_4$ source strengths of 25 to 85 mg $CH_4$ $m^{-2}$ $d^{-1}$ with aircraft boundary layer measurements, and established an averaged, seasonally adjusted source strength of 51 mg $CH_4$ $m^{-2}$ $d^{-1}$. A global estimate for tundra $CH_4$ emissions using this rate was 44 Tg $yr^{-1}$.

**NOWES/ABLE 3B.** The Northern Wetlands study (NOWES), a joint experiment between the Canadian Institute for Research in Atmospheric Chemistry (CIRAC) and the NASA Atmospheric Boundary Layer Experiment 3B, was conducted in 1990 to assess the importance of a large continuous wetland, the Hudson Bay Lowland in Northern Canada ($3.2 \times 10^{10}$ m$^2$), as a source/sink of biogenic gases under current climate conditions (Roulet *et al.*, 1992a). Most of the measurements of $CH_4$ flux in high latitude systems have been from relatively small isolated systems, i.e. wetlands with an area <1000 km$^2$. A dedicated issue (number D1) similar to the ABLE 3A issue of the *Journal of Geophysical Research* appeared in 1994.

The experiment was conducted in two locations. The first location was a 120 km transect running from James Bay coast inland to the interior of the Hudson Bay lowland. Areal coverage of this transect by wetlands and lakes was 100%. The second location was near Schefferville, Quebec, in a region that is approximately 30% wetland. Fluxes of $CO_2$, $CH_4$, $N_2O$, $NO_x$, and NMHCs were measured at numerous sites with flux chambers. A micrometeorological flux tower at each study site was used to measure fluxes of $CO_2$, $CH_4$ and $O_3$. Periodic boundary layer flux measurements of $CO_2$, $CH_4$, CO and $O_3$ were made by aircraft during the experiment. In addition to flux measurements, the concentrations of other trace gases such as $CO_2$, VOC, NO, $N_2O$, $NO_2$, $O_3$ and some NMHC were made throughout the summer at Schefferville and an atmospheric observatory on the southern fringe of the lowland.

Low $CH_4$ fluxes for the Hudson Bay Lowland were the most surprising result of the campaign. Based on prior studies (Bartlett and Harriss, 1993) the Hudson Bay Lowland was expected to emit between 5 and 7 Tg $CH_4$ yr$^{-1}$, but field measurements gave an estimate of 0.5±0.03 Tg $CH_4$ yr$^{-1}$. (Roulet *et al.*, 1994). These estimates were obtained by weighting chamber flux measurements by the fractional component of each major ecosystem determined by remote sensing. Fluxes measured by aircraft averaged 16 mg $CH_4$ m$^{-2}$ d$^{-1}$ (Ritter *et al.*, 1994), tower-derived fluxes averaged 16 mg $CH_4$ m$^{-2}$ d$^{-1}$ (Edwards *et al.*, 1994), and the modeled chamber fluxes averaged 20 mg $CH_4$ m$^{-2}$ d$^{-1}$. Methane fluxes measured by these three independent methods agreed to within a factor of 2 at all times, and to within a factor of 1.2 most of the time (Roulet *et al.*, 1993). However, Moore *et al.* (1993) have shown that comparisons between tower and aircraft fluxes to greater than a factor of 1.5 are not possible for sensible heat due to errors in measurements at different scales. These errors are larger in comparison to those for trace gases. The highest daily fluxes of $CH_4$ were from the shallow ponds on the surface of the wetlands: 40 to 150 mg $CH_4$ m$^{-2}$ d$^{-1}$. (Hamilton *et al.*, 1994). The fluxes from the peat surfaces were much smaller: <40 mg $CH_4$ m$^{-2}$ d$^{-1}$ (Moore *et al.*, 1994). Approximately 10% of the fluxes measured from the peat surfaces indicated uptake of $CH_4$. The NOWES $CH_4$ flux measurements were within 25% of those predicted by Fung *et al.* (1991).

The fluxes of $N_2O$ were small, −3.8 to 7.9 mg m$^{-2}$ d$^{-1}$, yielding a total source of ~1.2 GT yr$^{-1}$, an insignificant source in the global budget (Schiller and Hassie, 1994). Wetlands in general are $NO_3^-$ depleted and limited, so their capacity to yield large amounts of $N_2O$ is limited. The NMHC flux was measured in only a few locations, but was at least as large, and in many cases larger, than the $CH_4$ flux (Klinger *et al.*, 1994). The seasonal distribution of isoprene followed a pattern controlled by the source from vegetation and air temperature (Jobson *et al.*, 1994).

During NOWES there was little direct work on the controls of the fluxes of various trace gases. However, because the experiment was located along a transect in an area that has been isostatically rebounding since the last glaciation (Roulet *et al.*, 1992a), it presented an opportunity to study how 5000 years of peatland evolution influences the $CH_4$ flux. Moore *et al.* (1994) and Klinger *et al.* (1994) found clear relationships among various stages of ecological succession and $CH_4$ flux in individual wetland types, while Roulet *et*

*al.* (1994) showed there was a significant increase in $CH_4$ flux from the region of younger wetlands (1,000 to 2,000 years old) near the James Bay coast to older wetlands (~5000 years old) in the interior of the Hudson Bay lowland. This was in large part due to the increase in the area of shallow ponds on wetlands inland from the coast.

## Individual Studies

While the large campaigns have emphasized integration over large areas, individual studies have emphasized surveys, time series flux measurements, and processes controlling trace gas fluxes in a variety of high latitude wetland (Roulet *et al.*, 1992b; Roulet *et al.*, 1992c) and boreal forest (Whalen *et al.*, 1991) environments. These studies provide long term information on spatial and temporal variability of $CH_4$ fluxes; one study (Whalen and Reeburgh, 1992) has continued for 6 years, providing information on interannual variability. At least two of these studies have involved winter measurements (Dise, 1992; Whalen and Reeburgh, 1988). Winter fluxes are less than 5% of the annual emission in high latitude tundra systems, but can contribute as much as 20% of the annual emission in lower latitude peatlands with less extensive freezing. Scaling up site scale measurements to regional and global scales has involved areal weighting of fixed site time series flux data (Whalen and Reeburgh, 1988, 1992) and transect studies (Whalen and Reeburgh, 1990b). Measurements in an Alaska boreal forest system (Whalen *et al.*, 1991) showed that large areas of moist to dry soils actively consume atmospheric $CH_4$. Local bogs and fens are the only $CH_4$-emitting sites in boreal forest systems.

## Importance of High Latitude Systems in the Global Methane Budget

Because little was known about the $CH_4$ source strength of high latitude environments, a global emission estimate has been made using flux data from virtually every study. Table 1 summarizes these high latitude $CH_4$ emission estimates. Most of these studies assume an active period of 100 to 120 days and a distribution of environments related to the flux data available. Morrissey and Livingston (1992) point out that high natural spatial and temporal variability in fluxes make this practice questionable. The earliest estimate (Svensson and Rosswall, 1976) is based on a $CH_4$ flux/moisture relationship. The estimates of Sebacher *et al.* (1986) and Whalen and Reeburgh (1990b) are from transect sampling campaigns; the latter campaign involved sampling at fixed intervals to obtain an areally representative distribution of samples. Time series flux measurements from fixed sites were used in the estimates of Crill *et al.* (1988), Whalen and Reeburgh, (1988, 1992), and Moore *et al.* (1990). The estimate of Bartlett and Harriss (1993) results from a comprehensive review of published $CH_4$ flux data. Fung *et al.* (1991) used the GISS global 3-D tracer model, a compilation of geographic and seasonal $CH_4$ sources and sinks, and $CH_4$ carbon isotope ratios to provide constraints on global $CH_4$ budget terms. Several budget scenarios were tested for their ability to reproduce the meridional gradient and seasonal variations observed at the GMCC stations. Their preferred scenario calls for $CH_4$ emissions of 35 Tg $yr^{-1}$ from wetlands and tundra north of 50°. Reeburgh and Whalen (1992) pointed out that the high latitude $CH_4$ emission term seemed to be converging on about 35 Tg $yr^{-1}$. The additional global estimates since then, with the exception of the Bartlett *et al.* (1992) ABLE 3A estimate, lie between 20 and 45 Tg $yr^{-1}$ and have large (±50%) error limits. High latitude terrestrial environments contribute slightly less than 10% to the global $CH_4$ budget (Fung *et al.*, 1991).

**Table 1.** High latitude $CH_4$ emission estimates.

| Reference | Region | Location | Study Type | $CH_4$ Emission ($Tg\ yr^{-1}$) |
|---|---|---|---|---|
| Svensson & Rosswall (1976) | Arctic tundra | Stordalen, Sweden | summer fluxes extended with moisture relationships | 1 – 25 |
| Sebacher *et al.* (1986) | tundra and taiga | Alaska | flux transect, Arctic and boreal regions | 46 – 106 |
| Matthews & Fung (1987) | forested bog 50° – 70°N | — | estimated area × literature emission rates | 20 – 62 |
| | non-forested bog 50° – 70°N | — | estimated area × literature emission rates | 42 |
| Crill *et al.* (1988) | all bogs > 40°N | Minnesota peatlands | summer flux time series at permanent sites | 72 |
| Whalen & Reeburgh (1990) | Arctic tundra | U. of Alaska Arboretum | annual flux time series at permanent sites | 19 – 32 |
| Aselmann & Crutzen (1989) | wetlands 50° – 70°N | — | estimated area × literature emission rates | 23 |
| Moore *et al.* (1990) | northern fens | Quebec, Canada | summer flux time series at permanent sites | 14 |
| Whalen & Reeburgh (1990) | Arctic tundra | Alaska | flux transect, Alaska Pipeline Haul Road | 38 – 53 |
| | taiga | Alaska | flux transect, Alaska Pipeline Haul Road | 15 |
| Fung *et al.* (1991) | wetlands > 50°N | — | 3-D tracer model, estimates sources (scenario 7) | 35 |
| Whalen *et al.* (1991) | moist taiga | Bonanza Creek Exptl. Forest, Alaska | thaw season flux time series at permanent sites | – 0.8 |
| Whalen & Reeburgh (1992) | Arctic tundra | U. of Alaska Arboretum | annual flux time series (4 years of data) | 42 ± 26 |
| Bartlett *et al.* (1992) | ABLE 3A | Yukon-Kuskokwim Delta, Alaska | summer flux time series at permanent sites | 11 ± 3 |
| Ritter *et al.* (1992) | ABLE 3A | Yukon-Kuskokwim Delta, Alaska | aircraft boundary layer flux | 44 |
| Bartlett & Harriss (1993) | wetlands > 45°N | — | global summary | 38 |

## Present and Future Work

**North America.** *BOREAS.* The Boreal Ecosystem Atmosphere Study (BOREAS) is planned for 1994 at two locations in the boreal forest region of northern Canada. The objectives of the experiment are (1) to improve the understanding of the processes and states which govern the exchanges of energy, water, carbon and trace gases between boreal forest ecosystems and the atmosphere, with particular reference to those processes and states that may be sensitive to global climate change, and (2) to develop and validate remote sensing algorithms to extend this understanding of the processes from local to

regional scales. The focus of the research will be two 600 $km^2$ sites: one dry, warm boreal forest site located near Prince Albert in central Saskatchewan, and the other, a moist, cool boreal forest site located near Thompson, Manitoba. A unique aspect of BOREAS is the concurrent measurement of trace gases, tentatively CO, $CH_4$, some NMHCs, $N_2O$ and $NO_x$, and all important physical, biogeochemical and ecological variables at all the important ecosystems that comprise what would be considered the boreal biome. Using this approach, sites of both net emissions and uptake of trace gases can be quantified and the total influence of this portion on the boreal biome can be assessed. The ecosystems include various forest types (aspen, spruce, pine), wetlands, and beaver ponds. Measurements will consist of a full set of chamber, micrometeorological, and aircraft derived fluxes. The experiment will run from snowmelt to freeze-up in 1994, with three intensive measurement periods where all three types of flux measurements will be conducted simultaneously. One tower at each site will measure fluxes from August, 1993 to September, 1994.

*ARCSS/LAII Flux Study.* The NSF-sponsored Arctic System Science Land-Air-Ice Interactions Flux Study (ARCSS/LAII Flux Study) will be conducted along a transect in Alaska from Toolik Lake in the Brooks Range foothills to the Arctic Coastal plain from 1993 to 1996. The goal of this study is to understand the processes controlling carbon storage and emission as $CO_2$ and $CH_4$. This study will involve measurements of emission and consumption of $CO_2$ and $CH_4$ using micrometeorological tower and chamber studies, coupled with aircraft flux measurements at intervals during one field season. The gas flux studies are integrated with hydrologic and soil studies, vegetation mapping and spectral reflectance measurements for interpretation of satellite data in this multi-year project.

**Scandinavia.** Several programs examining trace gas fluxes are underway in Scandinavia and are projected to continue until 1998. A Swedish effort to quantify $CH_4$ fluxes from peatlands (Mikkelä *et al.*, 1992) also involves studies on the rates and controls on $CH_4$ production and oxidation (Svensson and Sundh, 1992). For example, Sundh *et al.* (1992) found that the oxidative capacity of a peatland is a direct function of the moisture content of the peatland. Other research is being conducted on the importance of peat quality on $CH_4$ flux (Nilsson, 1992) and the development of techniques such as FTIR for the measurement of the $CH_4$ flux.

Part of the Finnish Programme on Climate Change (SILMU) is examining the carbon balance of peatlands and climate change (Lainen and Päivänen, 1992). This experiment has been underway for three years and will continue for at least another three years. Chamber measurements of $CO_2$, $CH_4$ and $N_2O$ flux are being made in areas subjected to various treatments and manipulations to determine the controls on trace gas emissions (Lien *et al.*, 1992; Martikainen *et al.*, 1992; Silvola *et al.*, 1992). The project includes experiments related to gas exchange from northern wetlands such as the emissions of $CH_4$ from virgin and drained peatlands, the effect of drainage intensity on carbon and nitrogen mineralization, rate of net peat accumulation, response of Sphagna to N deposition and increased $CO_2$ concentrations, and organic carbon in peatland waters. A particularly unique aspect of these experiments is the use of forest drainage sites as surrogates for climate change.

**Russia.** Several groups have initiated $CH_4$ flux studies in various parts of Russia. Panikov and Zelenev (1992) are working in Western Russia, and Samarkin *et al.* (1992) are involved in studies in the Kolyma lowland. A program of $CO_2$ flux measurements is underway near Chernski, Yakutia (S. Zimov, private communication), and a $CH_4$ flux measurement program is being established there. Established field stations and ongoing expeditions in these areas should facilitate collaborative flux time series studies.

## CONTROLS ON HIGH LATITUDE TRACE GAS FLUXES (Task 2)

We understand in broad qualitative terms that $CH_4$ emissions result from a balance between production (methanogenesis) and consumption (methylotrophy). Physical factors that directly affect this balance are temperature, moisture, water table level, and substrate quality, but an understanding of the most important controls on $CH_4$ flux, the importance of feedbacks, and generally, the sensitivity of high latitude environments to altered climate remain unclear. Studies have concentrated on physical factors such as soil temperature because it is related to microbial activity, and the position of the water table, because it defines the zones of anaerobic (production) and aerobic (oxidation) processes. These are also the simplest variables to measure continuously.

Examples of relationships between $CH_4$ flux and soil temperature are summarized in Bartlett and Harriss (1993). A number of relationships have been reported for short term flux data sets using soil temperatures at fixed depths, but the number and variety of functions used (linear, polynomial, log-linear, and exponential), suggests that the relationship between temperature and $CH_4$ flux is not unique or straightforward (Whalen and Reeburgh, 1992).

Laboratory studies on the effect of water table level on $CH_4$ and carbon dioxide emission have been performed by Peterson *et al.* (1984) and Moore and Knowles (1987). Lowered wetland water tables are believed to control $CH_4$ fluxes by enhancing aerobic $CH_4$ oxidation. A lowered water table provides a more gas permeable surface zone that becomes aerobic through diffusive transport of atmospheric oxygen. This permits establishment of microbial populations capable of oxidation of $CH_4$ escaping from the deeper, waterlogged sediment layers. Whalen *et al.* (1993) showed that waterlogged tundra soils were anoxic only a few millimeters below the water table surface. Jar experiments with moist soils (Whalen and Reeburgh, 1990a; Whalen *et al.*, 1990) showed rapid equilibration with added tracers, suggesting gas phase diffusivities of $\sim 10^{-1}$ to $10^{-2}$ $cm^{-2}$ $sec^{-1}$, $10^4$ times more rapid than aqueous phase molecular diffusion. The $CH_4$ oxidizing populations responded rapidly to changes in $CH_4$ concentration and consumed $CH_4$ to threshold values of 0.1 ppm (Whalen *et al.*, 1992). Methane oxidation rates were very sensitive to water content, apparently a result of limiting transport by sealing inter-grain boundaries. The initial moist soil work suggested that oxidation could provide a rapid response and a negative feedback to increases in $CH_4$ flux.

The above rapid responses have not been observed in wetlands with waterlogged soils. Subsoil $CH_4$ distributions and fluxes appear to be decoupled, as high standing stocks of soil $CH_4$ and steep soil water $CH_4$ gradients show poor correlations with surface fluxes (Whalen and Reeburgh, 1992). Correlations between $CH_4$ flux and water table level in wetlands are generally poor, and appear to be masked in whole-season correlations (Whalen and Reeburgh, 1992). One possible explanation is that the $CH_4$ emission response occurs too rapidly to appear in whole-season correlations. The magnitude of $CH_4$ standing stocks in soil waters compared with the surface $CH_4$ fluxes suggests residence times of days. However, laboratory water table manipulation experiments on peat cores give results that suggest much slower responses. Moore and Roulet (1993) showed very dissimilar $CH_4$ flux responses under falling and rising water table conditions, and similar studies by Kizer and coworkers (private communication) showed that the $CH_4$ fluxes of cores subjected to water table adjustments stabilize only after periods of weeks. In contrast to the rapid response by moist soils, saturated or waterlogged soils show responses that may be related to flooding history or frequency. For example, in a falling water table situation, the newly exposed soils have only a history of anoxic conditions, and some time may be required to repopulate the zone with aerobic oxidizers. Reconciling the results of wetland field

observations with the laboratory core manipulations is an important problem that will require further study.

Whalen and Reeburgh (1992) noted that relationships between any single variable and $CH_4$ emission are site specific and of little value as predictors, emphasizing the fact that variables such as temperature and water table depth are not truly independent. They showed that parameters that integrate conditions over a season, such as thaw depth or centimeter degrees, correlated best with $CH_4$ emission on a given date. Dise *et al.* (1993) showed that the position of the water table explained over 60% of the variance in $CH_4$ flux in Minnesota wetlands using multiple regression. Temperature explained 30% of the variance and a measure of substrate quality explained the remainder. Moore and Roulet (1993) showed that the response of $CH_4$ flux to a unit change in water table is similar among wetlands, but that the actual flux for a given water table varies considerably. Systems with small changes in water table level over the study period show no significant relationship between $CH_4$ flux and water table (Moore *et al.*, 1994). When this is the case, peat temperature dominates the system (Roulet *et al.*, 1992c).

The above attempts are directed toward a process-level understanding of the factors controlling $CH_4$ flux. Considering parameters like biomass and primary production rather than variables like temperature and water table level appears to offer a promising means of predicting $CH_4$ flux from some wetland systems. Recent work in diverse wetland systems shows strong linear correlations between $CH_4$ emission and biomass (Whiting *et al.*, 1991) and $CH_4$ emission and primary production (Aselmann and Crutzen, 1989; Whiting and Chanton, 1993). All sites considered were inundated and populated with plants capable of vascular transport. Concurrent measurements of net primary production and $CH_4$ flux showed that approximately 3% of daily net primary production was released as $CH_4$ (Whiting and Chanton, 1993). The correlations between biomass and primary production could result from either litter input or production of suitable methane-forming substrates below-ground by root exudation and root turnover, or they could be a result of the plants providing conduits for $CH_4$ emission. This relationship offers the potential of estimates of $CH_4$ emission through remote sensing of either photosynthetic activity or net primary production. Further work suggested by the net primary production/net $CH_4$ emission relationship includes determination of the origin and age of the methane-forming substrate, the role of below-ground $CH_4$ oxidation (Reeburgh *et al.*, 1993), and the applicability of the relationship to non-inundated wetlands free of vascular plants.

## SENSITIVITY OF HIGH LATITUDE SYSTEMS TO CLIMATE CHANGE (Task 3)

Most climate models predict a large increase in winter temperature, and a moderate increase in summer temperature for northern regions. The predicted change in precipitation varies among models. Based on the output of the climate models, the summer climate of the northern wetland region is predicted to be warmer and slightly wetter, and it is not unreasonable to expect an increase in the annual emissions of $CH_4$ from northern wetlands. However, the biospheric feedbacks incorporating climate, hydrological and thermal regimes of wetlands, and the flux of $CH_4$ from wetlands are quite complicated and poorly understood. While an increase in summer precipitation would suggest an increase in the wetness of wetlands, the accompanying increase in temperature would also increase evaporative loss of water from wetlands. The direction of change in water storage in a wetland will be governed by the difference between precipitation input and evaporative and runoff outputs.

Models based solely on an increase in temperature suggest that the emissions of $CH_4$ from northern wetlands should increase in a $2 \times CO_2$ climate. Early models of Hameed and

Cess (1983) and Lashoff (1989) predicted an increase in $CH_4$ emissions with an increase in temperature. Harriss and Frolking (1992) developed a simple model based on the regressions of $CH_4$ flux and temperature developed by Crill *et al.* (1988) for peatlands in Minnesota. Using year-to-year temperature anomalies of ±2°C observed over the 20th century for five northern region wetlands, they estimate a ±5 Tg $yr^{-1}$ variation in emissions. This deviation represents only 15% of the total emissions from northern wetlands for the expected range of temperature increase predicted by most GCMs for a $2 \times CO_2$ climate and suggests only a moderate feedback.

The $CH_4$ temperature feedback models assume that the moisture status of the wetland remains the same. However, Roulet *et al.* (1992b) using a simple hydrothermal model for northern fens, estimated a decrease in moisture storage of between 60 to 200 mm in a $2 \times CO_2$ climate. The same model predicted a 0.8 to 2.0°C increase in the peat temperature. The increase in peat temperature resulted in a 15% increase in $CH_4$ flux, a result very similar to that of Harriss and Frolking (1992). However, the decrease in water storage resulted in an 80% decrease in $CH_4$ flux, suggesting that the emissions of $CH_4$ from northern wetlands are more sensitive to change in moisture than temperature. A small decrease in water storage in a wetland can easily offset any temperature-induced increase in emissions. The models used to estimate the $CH_4$ biospheric feedback for wetlands are preliminary and crude. Several studies have used empirical approaches to examine the climate-$CH_4$ feedback in wetlands, either by attempting to correlate seasonal and inter-annual variability in the $CH_4$ with climate variables, or by measuring the $CH_4$ flux from wetlands that have undergone some drainage. The results of two studies conducted in Alaska suggest that the $CH_4$ flux from wetlands is extremely sensitive to change in moisture and temperature. A four-fold variation in annual $CH_4$ emissions from wetlands in the interior of Alaska was observed over a four year period (Whalen and Reeburgh, 1992). Livingston and Morrissey (1991) compared the difference in the $CH_4$ flux from Alaskan North Slope wetland with varying moisture and temperature regimes between two years with very different climates. They found a four-fold increase in flux with a 4°C increase in soil temperature and an increase in wetness. They also found a two-fold increase in flux with a 4°C increase in soil temperature under drier conditions. These results suggest a far stronger sensitivity of the $CH_4$ flux to the climate than was found in modeling studies.

A criticism of the use of normal climate variability as a surrogate for climate change is that ecosystems should be well-adjusted to this type of variability. However, with a persistent change in climate, ecosystems should be pushed beyond the range of normal variability. To find the effect of persistent change in the moisture, Roulet *et al.* (1993) measured the flux of $CH_4$ from several wetlands that have been drained. These wetlands experience the day-to-day natural variability in temperature and precipitation, but have a lower mean water table than natural wetlands. Their results show that even a slight drop in water table of 0.1 m effectively eliminates the flux. The flux decreased from 5 to 10 mg $CH_4$ $m^{-2}$ $d^{-1}$ with an average water table of −0.2 m to between 0.1 and −0.4 mg $CH_4$ $m^{-2}$ $d^{-1}$ when the average water table was below −0.3 m. An additional drop in water table to −1.0 m did not increase $CH_4$ uptake. Whalen *et al.* (1993) used kinetic data on $CH_4$ oxidizers in soil cores to estimate that lowering the water table 10 to 40 cm could result in a zero net $CH_4$ flux.

All of the studies of biospheric feedback of $CH_4$ assume that there is no change in the structure and function of the wetland ecosystem. This is clearly a limiting assumption. Vegetation changes were obvious at the forest drainage sites used by Roulet *et al.* (1993) only after 10 years of drainage (J. Bubier, private communication) With changes in structure, changes in substrate quality and transport mechanism should be expected. Without an understanding of how the plant communities of wetlands respond to changes in

the climate it will be impossible to make any long-term predictions of future emissions from northern wetlands.

## FUTURE STUDIES

A remarkable amount of data on trace gas emissions from high latitude systems has been obtained in a relatively short time, and the importance of these systems as global $CH_4$ sources is converging on a value between 20 and 45 Tg $yr^{-1}$. A first-order understanding of biogeochemical processes controlling the balance between $CH_4$ production and emission has resulted, and models dealing with sensitivity of emissions to various observed parameters are under development. Future work should emphasize the following.

Our current information on high latitude trace gas fluxes has a strong North American bias, and has placed almost total emphasis on $CH_4$ emissions. Studies in northern European and Siberian wetlands are beginning, and should be supported with collaborative studies and flux time-series measurements. Obtaining flux data from these systems, based on accepted site classification and nomenclature used in the other high latitude studies, is essential to understanding the global importance of high latitude systems. It is important that future work emphasize measurements of not only $CH_4$, but also of other gases, particularly $CO_2$.

Estimates of the sensitivity of high latitude systems to climate change are only beginning. Most use historical climate data (temperature, rainfall) and simple relationships to flux. We appreciate that none of the driving variables are independent and that a single process-level parameter capable of predicting $CH_4$ flux is unlikely. Feedbacks promise to be an important control and require more study. Realistic manipulation experiments on the 1 to 10 m scale are needed to confirm process-level controls and their role in feedbacks. Preliminary experiments involving manipulation of water table level and temperature are underway and should be repeated in a range of environments. The design and eventual results of these experiments are critical to scaling models of biogeochemical feedbacks to general circulation models and chemical tracer models.

Understanding microbially mediated $CH_4$ production and oxidation in wetlands and soils should be a high priority. Understanding the origin of the substrates important in $CH_4$ production are needed for a process-level understanding of the methane flux:primary production relationship. There are very few direct measurements of $CH_4$ oxidation, but the available information suggests that oxidation may be about half of the gross $CH_4$ budget (Reeburgh *et al.*, 1993)

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