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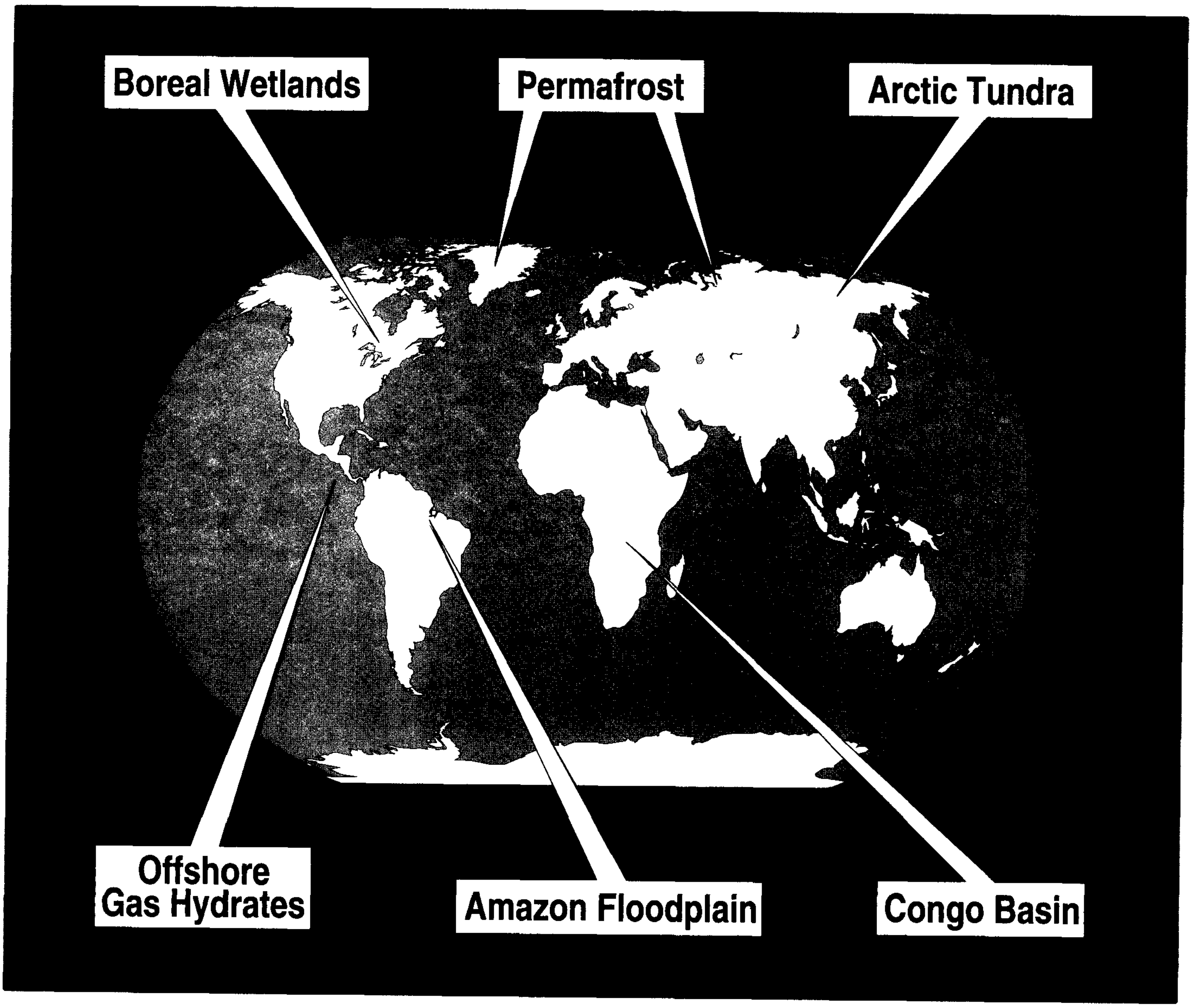
Current and Future Methane Emissions From Natural Sources

Report to Congress



Current And Future Methane Emissions From Natural Sources

Report to Congress

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U.S. Environmental Protection Agency
Office of Air and Radiation

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EXECUTIVE SUMMARY

This report is one in a set of reports requested by Congress in Section 603 of the Clean Air Act Amendments of 1990 to provide information on a variety of domestic and international methane issues. This report provides estimates of current and future methane emissions from natural sources.

Introduction

Methane is a "greenhouse gas," meaning that its presence in the atmosphere affects the earth's temperature. As a greenhouse gas, methane is a large contributor to potential future warming of the earth. Its concentration in the earth's atmosphere has more than doubled over the last two centuries (after remaining fairly constant for the previous 2,000 years), and continues to rise. Methane is second only to carbon dioxide in its contribution to potential future warming of the earth.

Methane's increasing atmospheric concentration is largely correlated with increasing human population. Human-related activities such as fossil fuel production, transportation, animal husbandry, rice cultivation, and waste management release significant quantities of methane, and all of these activities are expanding with industrialization and population growth. It is well established that these sources currently represent about 70 percent of total annual emissions. Natural sources account for the remaining 30 percent of methane emissions (See Exhibit ES-1).

While recent increases in atmospheric methane concentrations are largely attributed to human activities, variations in methane's atmospheric level over the previous 150,000 years are largely attributed to changes in methane emissions from natural systems, and in particular wetlands. This experience, in addition to other recent research, suggests that there is potential for the methane emissions from natural sources to increase as climate changes in the future. The emissions from several of the natural sources -- in particular, wetlands, gas hydrates, and permafrost -- are strongly governed by environmental variables such as temperature and precipitation. Therefore, climate change induced by humans could actually trigger the release of more greenhouse gases from natural systems. The implications of this effect are twofold:

- The rates and magnitude of future climate change would increase.
- The problem of controlling emissions of the greenhouse gases, so as to reduce the adverse effects of climate change, would be greatly exacerbated.

This report focuses on natural systems most likely to be sensitive to climate change: wetlands, gas hydrates, and permafrost.

This report investigates current methane emissions from natural systems by examining emission data that have become available in the last several years (and for the most part have not been reflected in

Exhibit ES-1

Natural Sources of Atmospheric Methane

Source	Emissions Estimate (Tg CH_4/yr)[1]	Range (Tg CH_4/yr)
Wetlands[2]	109	70-170
Termites	20	10-50
Oceans	10	5-20
Freshwater	5	1-25
Gas Hydrates	5	0-5
Permafrost	0	?
Total for Natural Sources	150	100-300
Total Methane Emissions[3]	505	400-610

Source: IPCC 1992.
[1] Tg = teragram = 10^{12} grams.
[2] taken from this report.
[3] Crutzen 1991.

IPCC[1] assessments). By further investigating recently available scientific information on the major processes governing methane emissions from these ecosystems, estimates of the potential for emissions to increase in the future, as a result of climate change, are developed. Emphasis is given to the three systems that are most likely to be affected by climate change -- wetlands, gas hydrates, and permafrost.

Current Methane Emissions from Wetlands, Gas Hydrates, and Permafrost

Wetlands represent between 4 percent and 8 percent of the earth's land surface and are currently the primary source of methane emissions from natural sources. Methane is generated in moist, oxygen-depleted, wetland soil by bacteria, as they decompose dead plant material. Emissions from gas hydrates and permafrost currently represent less than 4 percent of emissions from natural sources. However, they hold vast reserves of methane that may be liberated as temperatures rise.

[1] The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 under the auspices of the World Meteorological Organization and the United Nations Environment Program. Among other tasks, the IPCC was charged with assessing the science underlying the greenhouse effect. One assessment was published in 1990, and an update was published in 1992. Much of the data presented in this report is included in these science assessments, however, substantially more data has become available since their drafting.

Wetlands

Several recent studies have estimated that natural wetlands currently emit about 110 Tg of methane per year. These works include Matthews and Fung, 1987 (110 Tg/yr) and IPCC, 1990 (115 Tg/yr, with an uncertainty range of 100 to 200 Tg/yr).

In the last four years, many experimental studies were completed which greatly increase the number of available measurements of methane emissions from wetland systems. Many of these studies were performed in tropical and northern areas where there was previously very limited information.

Based on analyses in this report, which include this new data, wetlands worldwide are estimated to emit 109 Tg of methane annually. This global estimate is similar to past estimates of methane emissions from wetlands. However, a difference from previous studies is in the contribution to global emissions from each region. Here, 60% of wetland emissions are estimated to be from tropical systems, whereas previously tropical wetlands were only estimated to contribute 29% to 54% of the total. Systems in the northern latitudes now represent a smaller portion (35%) than in the past (31% to 58%), and temperate wetlands continue to represent a small portion (5%) of the total (see Exhibit ES-2).

Exhibit ES-2

Methane Emissions from Natural Wetlands

Wetlands Ecosystem	Area ($x10^{11}m^2$)	Annual Emissions ($Tg\ CH_4/yr$)		Percent of Total Emissions
		Value	Range	
Tropical	19	66	34-118	60%
Temperate	4.1	5	not available	5%
Northern	88.3	38	29-52	35%
Total	111	109	70-170	100%

Methane emissions from wetlands are grouped into major regions as follows:

Tropical Wetlands. Tropical wetlands (those between 20°N and 30°S) represent 17% of total wetland area and 60% of methane emissions from wetlands. These relatively high emissions are due to the higher temperatures and higher levels of solar radiation in the tropics as compared with other regions. Tropical wetlands will actively produce and emit methane anytime that there is sufficient precipitation to maintain inundation, or flooded conditions. The non-forested swamp system has the highest emissions of all tropical systems. This system is characterized by rapid plant growth rates and rapid decomposition, and average annual flux rates have been estimated at 85 g/m^2. The non-forested swamp system represents 42% of tropical wetland area and 52% of emissions.

Northern Wetlands. Northern wetlands (those above 45°N) are usually underlaid with near-surface permafrost which prevents soil drainage and thus creates flooded conditions. Temperature, or the length of the thaw season, largely determines when northern wetlands will actively emit methane, as opposed to tropical wetlands, where the emission period is determined by precipitation. The majority of emissions from this region come from inundated boreal (between 45°N and 60°N) and inundated arctic wetlands (above 60°N), with a small amount coming from well-drained arctic wetlands or tundra. The area and average emission rate from the two inundated wetland regions are almost identical, but the annual period of emissions is longer in the more southern boreal region. Therefore, inundated boreal wetlands account for 53% of northern emissions, compared with 37% from inundated arctic wetlands. The average annual flux rates have been estimated at 35 g/m^2. Also included in northern wetlands is well-drained arctic tundra. This expansive area (53% of all wetland area) is only marginally inundated and, thus, has a very low average annual emission rate (3 g/m^2). Well-drained tundra accounts for 10% of northern emissions and 4% of total wetland emissions.

Temperate Wetlands. Wetlands in the intermediate latitudes (between 20°N and 45°N, and between 30°S and 50°S) exhibit characteristics of both northern and tropical wetlands. However, because the temperature and rates of precipitation and solar radiation are lower in this region, and topographic relief is greater, temperate wetlands have lower emission rates than tropical wetlands. Because soil drainage tends to be better in the temperate zone, wetlands do not extend over nearly as large an area in the temperate region as in the far north. Temperate wetlands account for 4% of the total wetland area and 5% of total wetlands methane emissions.

Based on the analysis in this report, total wetland emissions may be as low as 70 Tg and as large as 170 Tg. This wide range arises primarily from the large variation in observed emission rates from similar ecosystems. For example, the emission rate for non-forested tropical swamps is estimated here to be anywhere from 52 to 285 mg CH_4/m^2/day. In general, the emission rate is sensitive to a number of variables including:

- the temperature, since methane-producing bacteria are generally more active as temperature increases;
- the level of the water table, since the area must be sufficiently flooded to maintain anaerobic conditions; and
- the plant community, since the plants affect the availability of carbon for decomposition, in addition to the transport of methane from the anaerobic zone to the atmosphere.

While large uncertainties in emission rates remain, the growing body of experimental information is beginning to show consistent results for experiments performed on similar wetland systems in different areas.

An attempt is also made to include the uncertainty in the total wetlands area in the range for total wetland emissions. This is accomplished by comparing two different surveys of wetland areas. However, uncertainty in the period -- the length of time that flooded conditions are maintained over the course of a year -- is not explicitly accounted for in the 70 to 170 Tg range. This source of uncertainty is not accounted for because no acceptable method has been found for quantifying the uncertainty in period.

Gas Hydrates and Permafrost

Gas hydrates and permafrost are two systems that currently contribute little, if any, to the annual emissions of methane. However, they both contain substantial reserves of methane and may contribute methane emissions in the future if climatic conditions change significantly.

Gas Hydrates. Methane can be trapped in gas hydrates, which are dense combinations of methane and water molecules located deep under the ground and beneath the ocean floor. An immense quantity of methane is trapped in both oceanic and continental gas hydrates, with estimates ranging from millions to billions of teragrams.[2] Extensive information is known about the temperature and pressure conditions required to maintain the stability of hydrates and keep the methane trapped. Scientists generally believe that the stability conditions have been altered for a small portion of the hydrates as a result of sea level rise which has occurred since the last major ice age. Calculations show that a relatively small amount of methane -- 3 to 5 Tg per year -- may be escaping to the atmosphere from this region.

Permafrost. Permafrost is ground, usually consisting of soil and ice, that remains at or below 0°C throughout the year for at least two consecutive years. Research has shown that methane is trapped in permafrost in small concentrations. Due to the large amount of permafrost that exists on earth, the total amount of methane stored in this form could be quite high -- possibly several thousand teragrams. While it has been proven that permafrost is melting in certain locations, no estimates have been made for current emissions from this source.

Future Methane Emissions from Wetlands, Gas Hydrates, and Permafrost

The emissions of methane from wetlands, gas hydrates, and permafrost are strongly linked to environmental variables, such as temperature and precipitation. While substantial uncertainty remains about how emissions from these systems will respond to changes in environmental variables, several of the relationships are becoming better understood. For example:

Precipitation. Inundation, or sufficient soil moisture, is a prerequisite for the anaerobic conditions that allow methane generation in wetlands. Increased precipitation could

[2] 1 teragram (Tg) is equal to 1×10^{12} grams or 1 million metric tons.

enlarge the area of land that is inundated and generating methane, as well as raise the average rate at which methane is generated on a unit area basis.

Temperature. A number of experiments have shown that methane emissions from a particular wetland area may increase exponentially with rising temperatures. Temperature is also the most important factor affecting the stability of gas hydrates and permafrost. If temperature rises, these two systems could be destabilized, and more methane released.

While changes in soil moisture and temperature are probably the most important variables that will determine future methane emissions, changes in several other environmental variables could play important roles. These include the species and density of plants, human land use impacts (particularly in tropical wetlands), the depth to permafrost in northern wetlands, and sea level rise. However, little work has been performed to assess the potential effects of these variables.

There are a number of predictions for how the climate might change over the next century. These projections are based on an effective doubling of carbon dioxide concentration in the atmosphere, which could occur by 2050. Projections have been made for increasing temperatures and changing precipitation patterns and may be summarized as follows:

- Global average temperature increases of about 1.9° to 5.2°C have been estimated for doubled carbon dioxide conditions (Mitchell et al., 1990). Regional and seasonal increases may vary. For example, temperatures increases of 4° to 8°C in northern latitudes during winter are expected. Tropical regions are expected to warm less, by about 2° to 3°C throughout the year.

- Precipitation increases globally, which could increase soil moisture in wetland regions. Conversely, a corresponding increase in evaporation due to higher temperature may lead to constant or decreased soil moisture.

Although there are still many uncertainties in these projections (and no predictions at all for some important environmental variables), they provide a useful basis for investigation of the effects that a continuation of current energy use and agricultural practices may have on methane emissions from wetlands, gas hydrates, and permafrost in the future.

Wetlands

While much uncertainty remains, climate change could cause methane emissions from wetlands to increase substantially within the next century. Potential increases in emissions are supported by two recent scientific workshops (Post 1990; this report) and work by Lashof (1989). These efforts developed rough quantitative estimates of possible increased emissions from northern wetlands. No predictions have been attempted for tropical wetlands.

Northern Wetlands. Methane emissions from these wetlands could increase significantly because northern wetland emissions are believed to be determined largely by temperature and because there is substantial carbon available, in the form of peat deposits, which could be liberated as methane in the future. Several scenarios are examined in this report. In one scenario, temperatures and precipitation increase, and wetlands become wetter due to more precipitation. In a second scenario, temperatures increase, and wetlands maintain their current water status as changes in precipitation and evaporation offset each other. In a third scenario, temperatures and *precipitation rise, but wetlands* become drier because evaporation increases by more than precipitation.

Although much uncertainty remains, researchers estimate that global warming could cause annual methane emissions from *northern wetlands* to increase by 5 to 300 Tg by the end of the century, depending on climatic conditions at the time.

Given these climate change scenarios, researchers have estimated the potential magnitude of future methane emissions. In all three scenarios, projected methane emissions will not decrease significantly and could increase by several fold within the next century (see Exhibit ES-3). While it is likely that the area of northern wetlands will be altered by future climate change, the predictions made to date do not account for any variations in wetland areas. (A change in wetland area could increase or decrease emissions.) This simplifying assumption is made because of the difficulty in predicting changes in wetland area.

Exhibit ES-3

Summary of Northern Wetland Emission Scenarios
(values shown are for increased emissions in Tg CH_4/yr)

Reference	Warmer/Drier	Warmer/Wet	Warmer/Wetter
Lashof 1989	--	17 - 63	--
Post 1990[1]	290	290	--
UNH Workshop[1]	5 - 35	35	65

[1] Expert workshops which emphasized best scientific judgement, due to limited experimental information in this area.

Tropical Wetlands. To date, predictions have not been made for future emissions from the tropics. Predictions for the tropics are even harder to make than are predictions for the north because emissions have not been shown to be strongly controlled by temperature. Future tropical wetland emissions will depend on several variables including regional precipitation, interactions between precipitation and actual evapotranspiration, and effects of human activities. However, it is not known how these variables will change in the future or exactly what their effect will be on methane emissions. Also, unlike most northern wetlands, a readily available source of carbon for increased emissions does not currently exist. While additional carbon could be supplied by increased plant activity, the likelihood of this outcome is unknown.

Gas Hydrates

Global warming could jeopardize the stability of currently stable hydrates, which contain thousands of teragrams of methane. While scientists disagree on the exact time lag before climate change would significantly affect the deeply buried hydrates -- estimates range from about one hundred years to a few thousand years -- there is a consensus that increasing temperatures will eventually destabilize much of the existing hydrates.

> **Although much uncertainty remains, scientists estimate that global warming could cause methane emissions from *gas hydrates* to rise from about 5 Tg/yr now to 100 to 1000 Tg/yr over the next few centuries.**

When warming does reach the hydrates there is a potential for tremendous quantities of methane to be released and for some of the methane to escape into the atmosphere. Several researchers have constructed scenarios of methane hydrate emissions to quantify the potential risk from this source. Results of these scenarios are increased emissions of 50 to 300 Tg CH_4/yr from continental hydrates and 150 to 640 Tg CH_4/yr from oceanic hydrates, beginning anywhere from one hundred to several thousand years from now. Because a variety of assumptions were used by the different researchers (including assumptions about future temperature increases), these scenarios are "adjusted" in Chapter 3 to reflect a common set of assumptions and arrive at composite scenarios for each type of gas hydrate. The composite scenarios derived in this report predict emissions of 100 Tg CH_4/yr from continental hydrates, and 200 Tg CH_4/yr from oceanic hydrates, with an uncertainty range of at least one order of magnitude. The average prediction of the time lag before emissions reach these levels is a few hundred years.

Permafrost

There is also potential for significant quantities of methane to be released from permafrost to the atmosphere in the future because large amounts of permafrost could melt due to rising temperatures in the polar regions. Permafrost releases are predicted to be smaller than hydrate releases, mainly because there is much less methane trapped in permafrost than in hydrate form. However, releases could be as high as 60 Tg CH_4/yr by the end of the next century.

> **Global warming could cause methane emissions from *permafrost* to reach 60 Tg/yr within the next century.**

Summary

Available information indicates that methane emissions from natural sources could increase by 5 to 370 Tg/yr by the end of the next century due to projected climate change. An increase of 5 to 370 Tg/yr is equivalent to about 100 to 7,000 million metric tons of CO_2, or an additional 0.2 to 17 percent of carbon dioxide beyond current predictions for the year 2100. Furthermore, due to the long delay before gas hydrate emissions will increase, natural methane emissions could increase by hundreds more teragrams annually in the centuries to follow the next one. The potential increases in emissions from northern wetlands, gas hydrates, and permafrost for different scenarios are summarized in Exhibit ES-4.

Climate change, as projected based on current patterns of energy use and agricultural practices, could trigger the release of an additional 5 to 370 Tg CH_4/yr from natural sources by the end of the next century. Further increases in methane emissions on the order of hundreds of teragrams annually could occur over the next several hundred years.

Uncertainties and Needs for Further Work

The generation, storage, transport, and release of biogenic methane are highly complex and variable processes. Scientists have only recently begun to understand the mechanisms of these processes and the potential for a natural methane feedback to climate change. Significant uncertainty surrounds many of the results presented in this report. With additional research in the field of natural methane emissions, this uncertainty can be reduced.

Wetlands

An important factor contributing to uncertainty in current emissions estimates is the wide variety of wetland types and the variability within each type. Understanding the magnitude and dynamics of methane emissions at one site of a certain type, does not necessarily transfer to other types or even other sites of the same general "type" that are geographically remote. While several independent studies have arrived at similar global methane emissions estimates despite the existing uncertainties, more field research could further reduce these uncertainties. This research should focus on systems not previously measured, in addition to developing better information on areas of different ecosystem types and periods of inundation.

Greater uncertainty exists in the future wetland emission scenarios. Not only are the relationships between methane emissions and environmental variables (e.g., precipitation, temperature, actual evapotranspiration, plant community, human impacts, sea level change) not well known, but how these environmental variables will change in the future is also uncertain.

The results of the three prediction efforts discussed here are not intended to be definitive, only rough ball-park estimates. They are based on the best available methods for estimation, which are crude, simplified methods. In some cases the calculations are reproducible because they are based on process based methodologies, in other cases the results are not reproducible because they are based on expert opinion of processes that have not been modeled. In the opinions of the scientists who developed them, the results are the reasonable estimates that can be made based on the information available at the present time. They are intended only to give policymakers a rough idea of the order of magnitude of the change in methane emissions from wetlands that could take place as a result of climate change.

Exhibit ES-4

Potential Increases in Methane Emissions from Selected Natural Systems due to Climate Change

System	Current Emissions ($Tg\ CH_4/yr$)		Range of Predicted Increases ($Tg\ CH_4/yr$)	
	estimate	range	within 100 yrs	after 100 yrs
Tropical Wetlands	66	34 - 118	0[1]	0[1]
Temperate Wetlands	5	n/a	0[1]	0[1]
Northern Wetlands	38	29 - 52	5 - 290	5 - 290
Hydrates (Continental)	5	0-5	0[2]	50 - 300[2]
Hydrates (Oceanic)	0	0	0[2]	150 - 640[2]
Permafrost	0	0	0 - 60[2]	0 - 60[2]
Total	114	70 - 175	5 - 370	200 - 1300

[1] In the absence of future predictions for these systems, they are assumed here to remain constant.
[2] The predicted increases for hydrates and permafrost are relatively more uncertain than the predicted increases for wetlands.

More field research, especially multi-year flux and environmental variable studies, will help clarify how methane emissions are controlled by factors such as water level and temperature. Natural ecosystem manipulation (artificially altering one variable in an otherwise unchanged natural ecosystem) and long-term monitoring of "early warning" or indicator ecosystems will also improve understanding of wetlands' response to climate change.

It is essential that process-based wetland models that incorporate the relationship between emissions and many environmental variables, not just temperature, are developed. Of course, such models can only be as good as the environmental data fed into them. Therefore, it is also important that site specific predictions for the important environmental variables can be made. As the scope and resolution of general circulation models increases and as process-based wetland models account for more environmental variables, future emission scenarios will become more reliable.

Gas Hydrates and Permafrost

In general, less is known about the topic of methane emissions from gas hydrates and permafrost than about wetland emissions. The greatest uncertainty surrounds future potential emissions from gas hydrates and melting permafrost. This uncertainty arises largely because gas hydrates, and especially permafrost, have only recently been recognized as potential sources of future methane emissions, and very little research has been performed to examine this possibility. An extensive sampling program of permafrost and sediment from the hydrate zone will help resolve some of the uncertainty surrounding methane reserve sizes. Additional research is also needed to better understand the mechanisms by which temperature changes are transmitted to the areas of trapped methane, and the processes by which released methane passes through the water and/or soil column to reach the atmosphere. While this uncertainty calls into question the timing and magnitude of fossil source emissions, it does not undermine the conclusion that significant emissions from fossil sources could occur as a result of climate change.

CHAPTER 1

INTRODUCTION

This report is one in a set of reports requested by Congress in Section 603 of the Clean Air Act Amendments of 1990 to provide information on a variety of domestic and international methane issues. This report provides estimates of (1) current methane emissions from natural sources worldwide, and (2) how these emissions may change in the future. Emissions are defined as methane that escapes into the atmosphere. This report is not intended to address the significance of methane in the atmosphere or natural sinks of methane.

1.1 Methane as a Greenhouse Gas

Methane (CH_4) is one of a group of atmospheric trace gases that plays an important role in atmospheric chemistry and in the earth's energy balance. Like other "greenhouse gases," methane traps outgoing infrared radiation from the earth's surface and increases the temperature of the earth. Methane is also a large contributor to potential future warming of the earth: its atmospheric concentration has more than doubled over the last two centuries (after remaining fairly constant for the previous 2,000 years), and its concentration continues to rise (IPCC 1992). CH_4 will contribute about 15 percent of this future greenhouse warming, second only to carbon dioxide (Rodhe 1990; IPCC 1992).

1.2 Present, Past and Future Sources of Atmospheric Methane

Methane's increasing atmospheric concentration is largely correlated with increasing human populations due to intensified and expanded activities such as the production and use of fossil fuels, animal husbandry, rice cultivation, and waste management. These sources currently represent about 70 percent of annual methane emissions (see Exhibit 1-1) (Cicerone and Oremland 1988; IPCC 1990; IPCC 1992). The remaining 30 percent of emissions are from natural sources of methane. Prior to the industrial age anthropogenic methane emissions were negligible (Chappellaz et al. 1992).

While increases in methane's atmospheric concentration in the recent past are largely attributed to human activities, changes in methane concentrations prior to the industrial age and spanning back over 150,000 years (as reflected in ice core data) are largely attributed to changes in emissions from natural sources.[3] Emissions from wetlands, in particular, are believed to have played a major role in almost doubling atmospheric methane levels twice

[3] Reliable historical data on the atmospheric concentration of methane are available from Antarctic and Greenland ice cores. The minimum concentration during the last glacial periods (about 20,000 and 150,000 years ago) was around 350 parts per billion volume (ppbv), and rose rapidly, in phase with the observed temperature increases to about 650 ppbv during the glacial-interglacial transitions (about 15,000 and 130,000 years ago) (Lorius et al. 1990; Raynaud et al. 1993; IPCC 1990). (The current atmospheric concentration of methane is about 1800 ppbv (IPCC 1990)).

Exhibit 1-1

Sources of Atmospheric Methane

Sources	Estimate ($Tg\ CH_4$/year)	Range
Natural		
Wetlands[1]	115	100-200
Termites	20	10-50
Oceans	10	5-20
Freshwater	5	1-25
Gas Hydrates	5	0-5
Anthropogenic		
Coal Mining, Natural Gas & Petroleum Industry	100	70-120
Rice Farming	60	20-150
Domesticated Livestock	80	65-100
Livestock Manure	25	10-20[3]
Wastewater Treatment	25	20-25
Landfills	30	20-70
Biomass Burning	40	20-80
Total[2]	505	400-610

Source: IPCC 1992.
[1] New estimates for wetland emissions are developed in Chapter 2 of this report.
[2] Estimation based on observation of atmospheric concentrations rather than sum of individual sources shown here (Crutzen 1991).
[3] Emissions from Livestock Manure reflect revised estimates. Emissions for all other sources are currently being updated by EPA (1993)

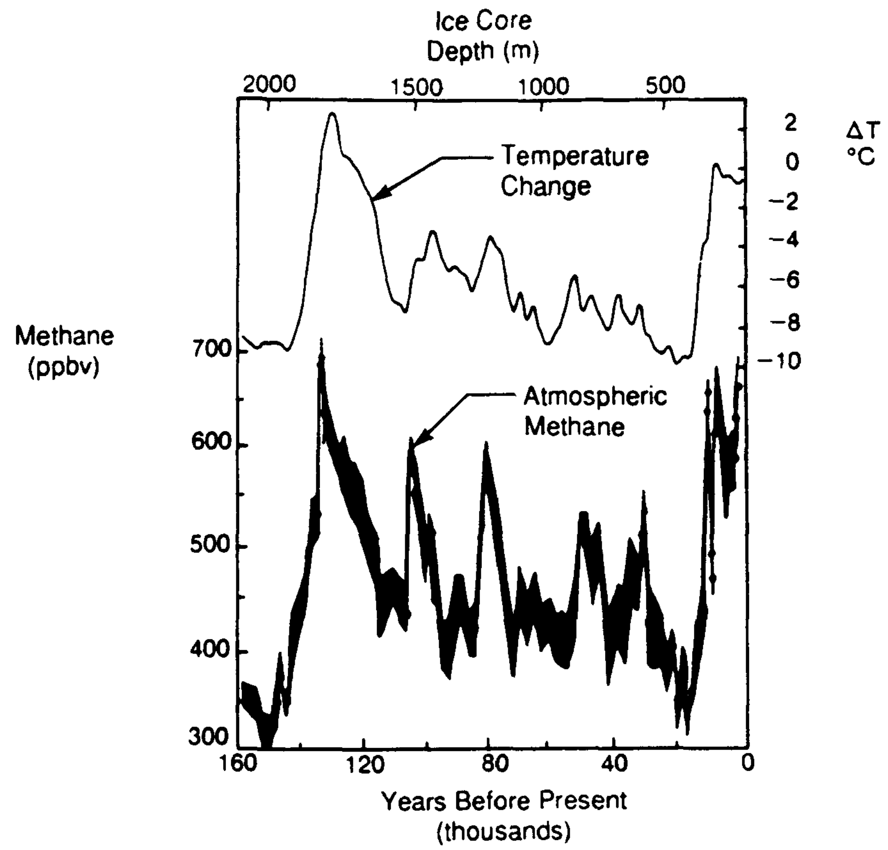
during this period.[4] Increased emissions from gas hydrates have also been proposed as a reason for the historical rise in atmospheric methane concentration (Nisbet, 1992). Exhibit 1-2 shows the atmospheric methane concentrations (bottom line - right scale) and estimated temperature changes (top line - left scale) during the past 160,000 years as determined on

[4] Chappellaz et al. (1992) estimate that natural wetland emissions rose from 75 Tg CH_4/yr during the Last Glacial Maximum (18,000 years before the present) to 135 Tg CH_4/yr during the Pre-Industrial Holocene (9000 - 200 yrs BP).

the ice core from Vostok, Antarctica. In total, ice core records suggest that a global increase in temperature of 1 °C causes an increase in atmospheric methane levels of about 50 ppbv under natural conditions (Raynaud et al. 1993). Assuming an atmospheric lifetime of 10 years, this finding suggests that natural methane emissions increased by about 15 Tg/yr for each 1 °C increase in temperature.

Exhibit 1-2

Methane Concentrations and Temperature Changes in the Past 160,000 Years



Source: Chappellaz et al. 1990

The past ice core record, in addition to other recent research, suggests there is potential for the methane emissions from natural sources to increase as climate changes and further contribute to increasing atmospheric concentrations of methane. The emissions from several of the natural sources -- wetlands, gas hydrates, and permafrost -- are strongly governed by environmental variables such as temperature and precipitation. As these environmental variables are altered through climate change, emissions from natural sources could increase and act as a positive feedback to further fuel increasing global temperatures.

1.3 Current Emissions from Natural Systems

The largest source of natural methane emissions is natural wetlands. Smaller contributors to natural methane emissions include gas hydrates, permafrost, termites, oceans, and freshwater. Natural wetlands, gas hydrates, and permafrost regions are likely to play the largest roles in altering future methane emissions from natural sources as a result of climate change, and therefore are the focus of this report.

Natural Wetlands

Like agricultural wetlands such as flooded rice fields, natural wetlands are significant sources of methane. They provide a habitat conducive to methane-producing (methanogenic) bacteria that produce CH_4 during the decomposition of organic material. These bacteria require environments with no oxygen (a situation promoted by flooded soils) and abundant organic matter, both of which are characteristics of wetlands (Zehnder 1978).

The process by which wetlands emit methane involves the methanogenic bacteria and methane-consuming (methanotrophic) bacteria. Net emissions to the atmosphere are equal to methane production by methanogens minus consumption by methanotrophs.

Emission (Net) = Production (Gross) - Consumption

More specifically, methane is produced by methanogens in the anaerobic layer of wetland soil (Exhibit 1-3).[5] Once produced, most of the methane enters the aerobic soil layer and is oxidized (converted to carbon dioxide and water) by the methanotrophs present in that layer.[6] Methane that is not oxidized in the aerobic layer eventually reaches the atmosphere by one of three transport mechanisms. The primary transport mechanisms for the methane vary among wetland systems with some methane exiting through the plant, some collected in air bubbles that migrate to the surface, and some undergoing molecular diffusion through soil and water to reach the atmosphere (Exhibit 1-3). Notice that in this exhibit the water table is above the soil surface, which is common in tropical systems, however, in many cases, particularly in northern ecosystems, the water table may be below the soil surface.

Currently about 4 percent of the land surface of the earth is inundated wetlands which produce and emit methane. These wetlands are concentrated in the high latitudes of the far north and in the tropics (Exhibit 1-4). In the north during the thaw season, permafrost below the soil surface impedes soil drainage and causes the flooded conditions conducive to methane production. In the tropics high rates of precipitation at any time during the year lead to flooded conditions. Temperate-zone wetlands can exhibit the characteristics of both tropical and northern wetlands.

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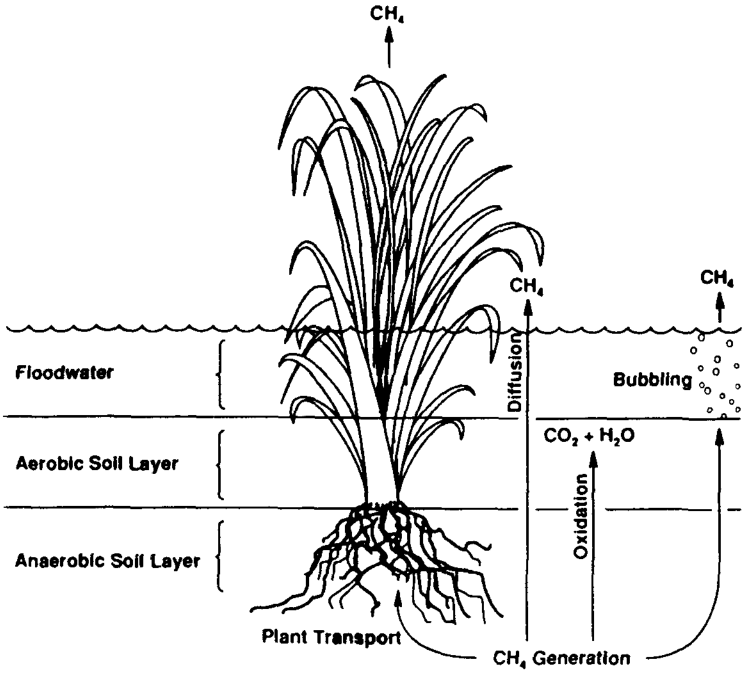
[5] The method by which methane is produced in an anoxic ecosystem is a complex process generally referred to as an "anaerobic food web". In this process a variety of nonmethanogenic anaerobic microbes attack complex organics, resulting in the formation of methanogenic substrates. Theses substrates are then metabolized by the methanogenic bacteria into methane (Cicerone and Oremland 1988).

[6] Studies have shown that methane can be oxidized in the anaerobic layer as well as the aerobic layer (Cicerone and Oremland 1988).

Exhibit 1-3

Methane Emissions Pathways



Wetlands can be forested or unforested. All forest ecosystems that emit significant amounts of methane are accounted for this report under natural wetlands. The vast majority of wetlands are freshwater, as opposed to saltwater. In fact, the only saltwater wetlands that emit appreciable quantities of methane are saltwater marshes in the temperate zone. These systems are included in the analysis here for temperate wetlands.

In addition, moist to dry tundra in the arctic has been identified as a source of methane emissions. While dry or well-drained tundra has not been considered a wetland in some other efforts, it is considered a source in this report due to potential current emissions and due to the potential for emissions to change as climate is altered. The area of well-drained tundra, is about 5.9×10^{12} m^2 (or another 4 percent of the land surface area on earth), for a total wetland area of 111×10^{12} m^2 (see Exhibit 1-5).

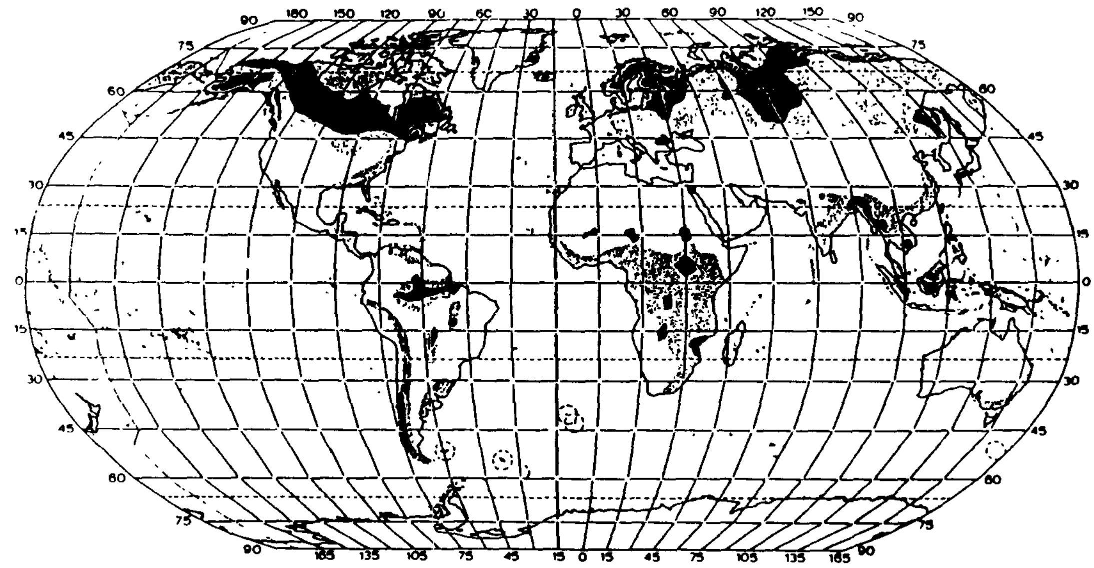
Recent studies have estimated that natural wetlands emit about 110 Tg of methane per year (Matthews and Fung 1987; Aselmann and Crutzen 1989). However, substantial additional observational data have become available over the last several years, and new estimates for emissions for the different regions of natural wetlands are developed from this data in this report.

Fossil Sources

The other natural sources of interest, gas hydrates and permafrost, are fossil sources of methane, meaning that the methane was created in the geologic past, stored in the earth's

Exhibit 1-4

Wetlands Map



KEY
dark shading: wetland area > 10%
light shading: 0.5% < wetland area < 10%
dashed circles: islands with substantial wetland areas
(Source: Hofstetter 1983)

Source: Hofstetter (1983)

Exhibit 1-5 Global Wetland Area

Latitude Region	Area ($x10^{11}m^2$)
Tropical Wetlands (30°S-20°N)	19
Temperate (45°-20°N, 30°-50°S)	4.1
Northern Wetlands (above 45°N)	29.6
Total Inundated Wetlands	52.6
Well-drained Arctic Wetlands (Tundra)	58.7
Total Wetlands	111

crust, and is only now being released to the atmosphere. Fossil methane can be released by a variety of activities, including natural gas systems and coal mining operations; however, these emissions are triggered by human rather than "natural" activity, and thus are classified as anthropogenic emissions. Seepage from natural gas reservoirs is a natural fossil source, but currently there is little information available on the importance of this source. Thus, emissions from two sources, gas hydrates and permafrost, represent the larger natural fossil sources of methane.

Hydrates. Hydrates are solids composed of cages of water molecules that contain molecules of methane. They are found deep underground in polar regions (continental hydrates) and in ocean sediments of the outer continental margin throughout the world (oceanic hydrates) (see Exhibit 1-6). A vast amount of methane is stored in hydrates. The exact amount is not known but is probably around 10^7 Tg for oceanic reserves and $5x10^5$ Tg for continental reserves. Recent estimates of current emissions from hydrates range from 0 to 5 Tg per year (Kvenvolden 1991e; IPCC 1992).

Historically, major changes in surface conditions of the earth, such as ice ages, have caused huge quantities of methane (i.e., thousands of teragrams) to move into and out of hydrates. These movements typically take place over the course of thousands to tens of thousands of years, and have altered the climate-controlling radiative properties of the earth. It has been hypothesized, for example, that the release of methane from hydrates significantly contributed to the warming which caused the last major ice age to come to an end (Nisbet 1990; MacDonald 1990).

Permafrost. Permafrost methane is created mainly through biological processes and trapped in shallow permafrost ice and soil before it can reach the atmosphere. Permafrost underlies about a quarter of the land area of the earth. The amount of methane stored in permafrost is not well known, but based on the range of observed concentrations of methane in permafrost samples, there could be over 5,000 Tg in the ice portion of permafrost alone. The average total volume of permafrost is known to be decreasing in limited areas. The volume of permafrost that is being lost and the volume of methane being released as a result have not been calculated. Large quantities of organic matter are also frozen in the permafrost. If thawed, this organic matter could increase methane generation in the active soil layer. (This possibility is accounted for in the chapter on natural wetland emissions.)

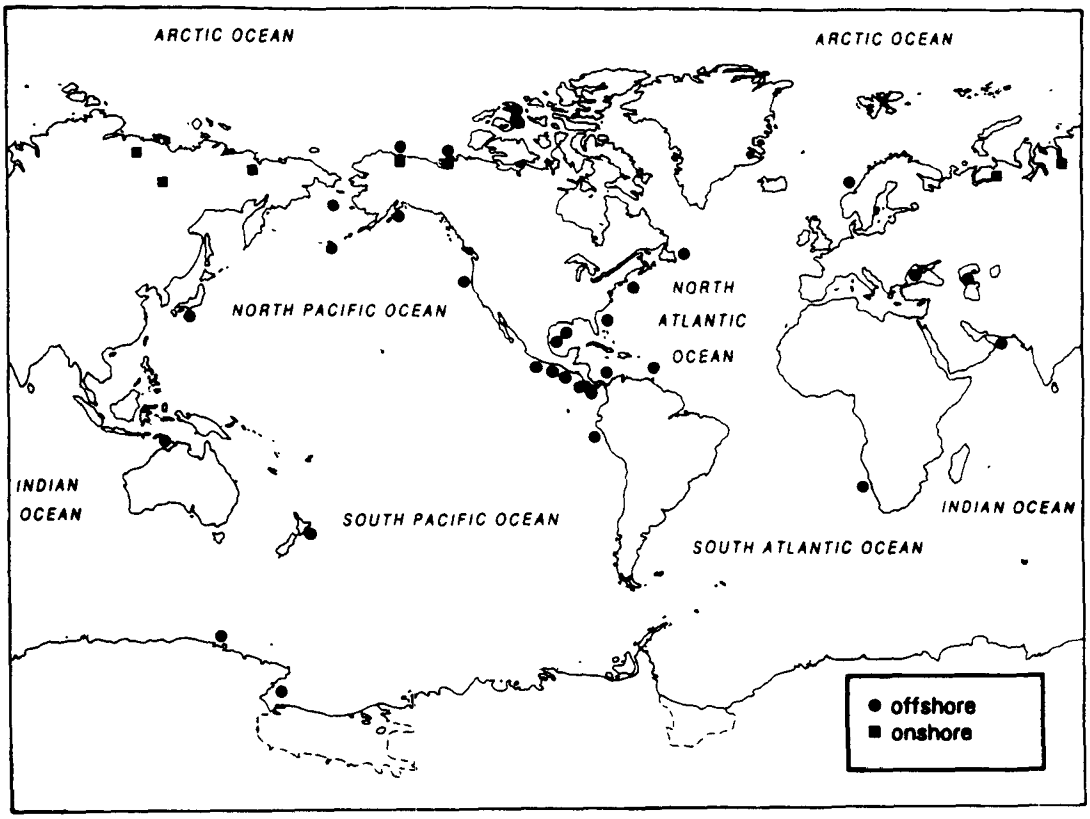
Other Natural Sources

Several other sources of methane from non-fossil, natural sources are known or inferred to exist. While these sources have not been well researched, it is generally believed that they are relatively small ones. Furthermore, it has not been hypothesized that emissions from them are likely to increase as a result of climate change. Therefore, this report does not discuss potential future emissions from these sources. Additional research is necessary to better understand current emissions from these systems and how they are likely to respond to changes in climate.

Termites. Recent studies have scaled back estimates of methane emissions from termites from 10 to 100 Tg/yr to 10 to 50 Tg/yr (IPCC 1992). Emissions from this source are dependent upon termite population, amounts of organic material consumed by termites in various biomass, species differences, and activity of methane-oxidizing bacteria (Cicerone and Oremland 1988). While more research needs to be done in this

Exhibit 1-6

Locations of Known or Inferred Gas Hydrates



Source: Kvenvolden (1988)

area, some experts believe that future trends in termite emissions are far more likely to be shaped by anthropogenic changes in land use (e.g., deforestation for agriculture) than by climate change (Nisbet and Ingham, submitted; Bartlett, pers. comm. 1993).

Oceans and Freshwaters. Research conducted in the late 60's and early 70's established that the surface waters of the world's oceans are slightly supersaturated with methane in relation to its partial pressure in the atmosphere, and therefore are currently emitting methane. In other words, the carrying capacity of the oceans has been exceeded. The emission estimate of 5 to 20 Tg/yr in Exhibit 1-1 may be high because the atmospheric concentration of methane has probably increased 20% since this range was developed in 1970, thereby increasing the carrying capacity of the oceans (Cicerone and Oremland 1988). The source of the methane emitted from the oceans is not clear. In coastal regions it could come from sediments and drainage (e.g., rivers). It has also been suggested that methanogenesis occurs within the anaerobic gastrointestinal tracts of marine zooplankton and fish (Cicerone and Oremland 1988). In freshwaters, methane emissions can result from the decomposition of wetland plants. These emissions are accounted for in this report under wetland emissions. Additional source(s) of methane from freshwaters are believed to exist but very little is known about them. At this time, there is no published information that suggests that emissions from oceans and freshwaters will increase in the future.

Non-Wetland Soil Emissions. There are several ecosystems which do not fall under the category of wetlands as used in this report, but are believed to emit methane, at least in some areas, over some period of time. An example might be relatively well-drained, boreal forests that are water-saturated after snow-melt (Bartlett, pers. comm. 1993). However, emissions from these systems are not considered significant because they have not been included in any of the published studies of methane sources (Matthews and Fung 1987; Cicerone and Oremland 1988; Fung et al. 1991).

1.4 Future Emissions from Natural Sources

Emissions from natural sources are strongly influenced by environmental variables, such as soil temperature and inundation (water level), which will be affected by climate change. Natural methane emissions may, therefore, represent a positive climate feedback process. Climate change induced by humans could trigger the release of more greenhouse gases from natural systems. The implications of this effect are twofold:

- The rates and magnitude of future climate change would increase.
- The problem of controlling emissions of the greenhouse gases, so as to reduce the adverse effects of climate change, would be greatly exacerbated.

Feedback processes are natural systems that have the ability to amplify or dampen the initial change in radiative forcing caused by increasing concentrations of greenhouse gases. There are two types of feedbacks: (1) geophysical feedbacks are part of the internal physical dynamics of climate; and (2) biogeochemical feedbacks deal with the earth's biology and chemistry.

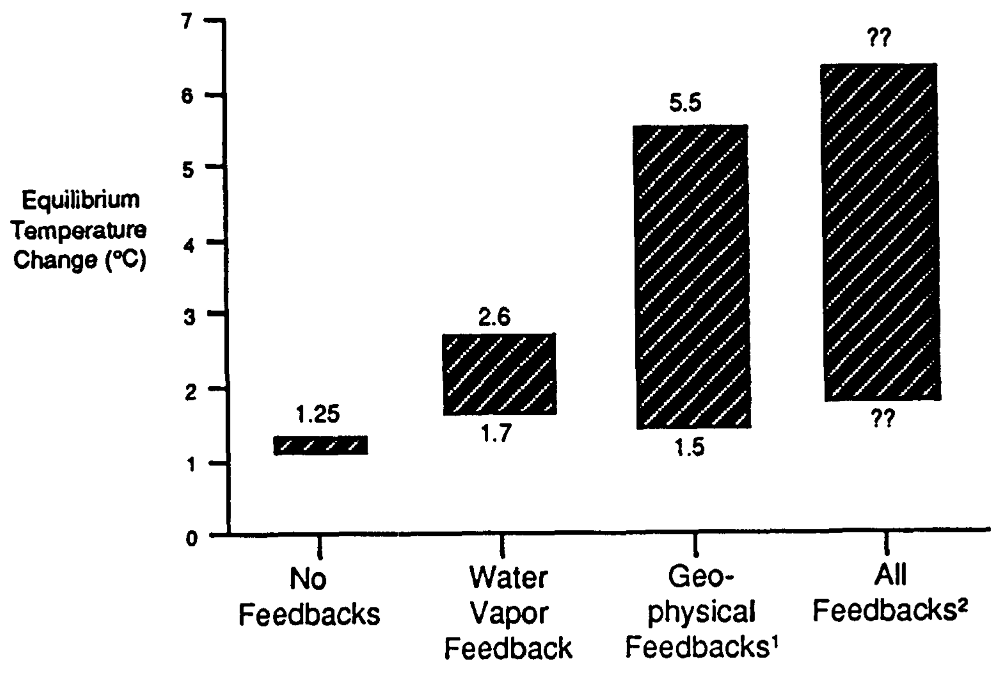
The more important geophysical climate feedbacks -- water vapor, clouds, and sea ice albedo -- are accounted for in current efforts to predict climate change through the use of Global Circulation Models. For example, the water vapor feedback is modeled by estimating the additional water vapor that the atmosphere can hold as it warms. The additional water vapor, which is a greenhouse gas, amplifies the initial warming. This positive feedback acts to approximately double the initial warming of the atmosphere that would result from human activities alone (EPA 1990). Biogeochemical feedbacks, such as changes in natural methane emissions, ocean CO_2 uptake, and vegetation albedo, have generally not been included in the climate models (Lashof 1989).

The ability to quantify the impact of biogeochemical feedbacks is limited by the current understanding of these systems.[7] However, these feedbacks could contribute to a substantially larger potential warming than is now predicted by climate models. As Exhibit

[7] Analyses of ice core data indicate that natural sources of methane may have provided significant feedback to climate changes in the past (Raynaud et al. 1993).

Exhibit 1-7

Climate Feedbacks to Doubled CO_2 (Based on 1.5 to 5.5 Degree Sensitivity)



1 Includes: Water Vapor, Ice and Snow, Clouds
2 Includes: Geophysical Feedbacks and Biogeochemical Feedbacks (Natural Methane, Ocean Effects and Vegetation Effects)
Sources: Lashof (1989); EPA 1990

1-7 illustrates, climate models generally predict that temperatures will rise approximately 1.2°C (within 50 to 100 years) as a result of the emissions from human activities alone, with a doubling of greenhouse gases in the atmosphere (CO_2 equivalents). When the water vapor feedback is added, temperatures are predicted to rise to 1.7° to 2.6°C. When ice, snow, and clouds are added, the models predict temperatures to rise by 1.5° to 5.5°C (EPA 1990). The temperature rise if all feedbacks -- geophysical and biogeochemical -- are included is highly uncertain, but it is likely to be greater than the temperature rise when only geophysical feedbacks are considered (Lashof 1989).

1.5 Overview of this Report

In the Clean Air Act Amendments of 1990, Congress requested that the U.S. Environmental Protection Agency investigate the extent to which natural methane emissions may provide a positive feedback to climate change, and to prepare a report to Congress for submission no later than two years after enactment of the Act on:

- methane emissions from biogenic sources such as (a) tropical, temperate, and subarctic forests, (b) tundra, and (c) freshwater and saltwater wetlands; and

- the changes in methane emissions from biogenic sources that may occur as a result of potential increases in temperatures and atmospheric concentrations of carbon dioxide.

This report was prepared to fulfill the above request.[8] The report reviews the state-of-the-art for estimating emissions of methane from natural systems to the atmosphere and understanding the factors controlling emissions from these systems. The report also attempts to identify a set of possible changes in emissions from natural systems in response to a changing climate.

This report is divided into two major sections:

Chapter 2: Natural Wetlands. This chapter reviews methane emission data collected from wetlands worldwide, provides average emission rates for different wetland ecosystems, develops global emission estimates, presents some possible future scenarios, and discusses further research that could reduce uncertainty in the developed estimates.[9]

Chapter 3: Fossil Sources. This chapter -- divided into gas hydrates and permafrost -- describes the different systems, provides available estimates of current emissions, presents scenarios for future emissions, and discusses the major uncertainties and how they could be resolved.

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[8] The congressional request also asked for interagency coordination of the development of the methane reports. This coordination was accomplished through formation of an Interagency Working Group on Methane which met quarterly to discuss important issues.

[9] Much of the information for this chapter was developed through a grant from the EPA to the University of New Hampshire and the efforts of R. Harriss, K. Bartlett, and P. Crill. (A separate article is being submitted by these researchers for publication in a scientific journal.) In order to assess the potential impacts of climate change on natural wetlands, a workshop was held at the University of New Hampshire on March 10 and 11, 1992, as part of the EPA grant. A list of the wetlands researchers who participated in this workshop is provided in Appendix A.

CHAPTER 2

NATURAL WETLANDS

Natural wetlands is a general term for a broad range of unique ecosystems. To determine the global annual emissions of methane from wetlands a classification system is developed by which wetlands ecosystems with similar methane emissions characteristics can be reasonably aggregated into general wetland types. The areas, average emission rates, and annual period of emissions for these wetland types are then calculated.

2.1 Background -- Wetlands Classification

Wetlands are commonly divided by latitude into three major regions: tropical, temperate, and northern. Fundamental differences exist in the physical and climate processes that characterize tropical and northern systems; temperate systems can exhibit the characteristics of either tropical or northern systems.

In the tropics, high rates of precipitation lead to flooded conditions in low-lying areas, such as river basins. These high precipitation rates, coupled with the high temperatures and solar radiation rates in the tropics, are conducive to plant growth and decay. In areas of inundation, this decay process produces methane, which can be released into the atmosphere. Thus, methane is emitted year-round in permanently inundated wetlands and during the inundation period in wetlands inundated only seasonally.

In the northern region, wetlands are common because permafrost exists just below the soil surface and inhibits the drainage of moisture from the upper soil layer. While recently discovered evidence suggests that some methane may be emitted from northern wetlands in the winter, northern wetlands generally only emit methane during the summer, the thaw season. These wetlands also differ from tropical ones in that they generally contain large peat deposits (partially decomposed plant residue).[10]

The division of wetlands into tropical, temperate, and northern is a generalization that alone does not adequately characterize wetlands in terms of methane emissions, since fluxes vary widely within these regions as determined by vegetation or habitat type. Therefore, additional subdivisions by vegetation type have been developed. These subdivisions have been chosen to maintain relatively homogeneous systems and assist in developing methane emission estimates. These further subdivisions are discussed below in terms of their major characteristics, their relative emissions of methane (discussed in detail in section 2.2), and their areal extent.

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[10] The accumulation of peat indicates that at a particular location and moment in time the rate of plant matter deposition is greater than the rate of anaerobic decomposition (e.g., that some variable other than organic matter is the limiting variable in the decomposition equation). The presence or absence of peat does not necessarily indicate the size of methane emissions. However, it is important information for developing future emission scenarios because peat is an existing source of carbon which can be converted to methane if certain conditions are met in the future.

2.1.1 Tropical Wetlands

Wetlands in the tropics (roughly 20° N to 30° S) are generally characterized by relatively high methane emission fluxes. The high methane emission rates result from a rapid cycle of plant growth and decomposition due to high temperatures and elevated levels of solar radiation. However, emissions vary substantially for different ecosystems. For example, ecosystems with limited vegetation and in alluvial (flowing water) settings have less available carbon for decomposition and relatively low emissions. To define homogeneous systems for estimating methane emissions, tropical wetlands can be divided into three distinct categories each with a specific area of coverage:[11,12]

Non-forested Swamps. Non-forested swamp wetlands generally have the highest emission rates of the tropical systems. These wetlands are found mostly in the Amazon floodplain and contain several species of grass which have adapted to seasonal inundation. These species have high growth rates over much of their life cycle in order to maintain access to sunlight. Grasses eventually break away from the submerged soils and float freely in large mats. Non-forested swamps are also generally not alluvial and are peat-poor. Non-forested swamps are estimated to extend over 7.9×10^{11} m^2, comprising 40% of tropical wetlands, and 15% of global inundated wetlands.[13]

Flooded Forests. Flooded forests, sometimes referred to as forested swamps, tend to emit more methane than unvegetated open water, but less methane than grassy wetlands. They can be seasonally or permanently inundated. For example, extensive seasonal wetland areas may occur in the flood plains of large rivers such as the Amazon. Flooded forests are usually characterized by minimal peat deposits and by standing water, but they are occasionally rich in peat and/or alluvial. Flooded forests are estimated to cover 10.4×10^{11} m^2 in the tropics, comprising 55% of tropical wetlands and 20% of global inundated wetlands.

Open Water. Open water wetlands are the smallest category of tropical wetlands and have the lowest emission rates. They generally lack vegetation and can be seasonally

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[11] Areas for the different ecosystems were derived from Matthews and Fung (1987), who divided wetlands into 10° latitude bands, and areas within each band, into 5 wetlands classifications: forested bog, non-forested bog, forested swamp, non-forested swamp, and alluvial wetland formations. Bogs are usually rich in peat, while swamps are peat-poor. Unlike bogs and swamps, alluvial formations are characterized by flowing surface water. The total wetland area from Matthews and Fung (1987) is preserved in this report and simply categorized differently according to this classification system. The following correlations have been made between tropical wetland types used by Matthews and Fung (1987) and the breakdown described above:
- Non-forested swamps (in this report) = non-forested swamps + non-forested bogs + one third of alluvial formations (in Matthews and Fung).
- Flooded Forests = forested swamps + forested bogs + one third of alluvial formations.
- Open Water = one third of alluvial formations.

[12] This classification system has been developed to correspond to the current set of measurements from tropical regions. As new measurements are taken in different systems, this classification system may be modified.

[13] The area of each wetland category is compared to global inundated wetlands rather than total wetlands (inundated + well-drained arctic tundra) because well-drained tundra has not been considered a wetland in several previous studies, and therefore this comparison is more useful for cross-referencing.

or permanently inundated. Open water wetlands are estimated to cover $0.5x10^{11}$ m^2, which is 3% of tropical wetlands and 1% of global inundated wetlands.

2.1.2 Temperate Wetlands

While a wide variety of wetland types are found in temperate to subtropical regions (45°-20° N and 30°-50° S), these regions account for only about 7% of the total inundated wetland area ($4.1x10^{11}m^2$). Temperate wetlands generally produce much less methane per unit area than tropical systems, in part due to lower temperatures and lower solar radiation. For this analysis, temperate wetlands are grouped into the four categories used by Matthews and Fung (1987) to describe this region:

Forested Bogs. Forested Bogs generally have the highest emission rates of the temperate systems. They are dominated by shrub wetlands (evergreen and drought-deciduous) and high-latitude, temperate, boreal forest/woodland/shrub wetlands. In general, bogs have significant peat deposits. The areal extent of these bogs is estimated at $1.0x10^{11}$ m^2, or 2% of global inundated wetlands.

Forested Swamps. Forested swamps in the temperate zone are wooded wetlands, usually with minimal peat accumulation. Average emissions are considerably less than those of forested bogs.[14] The area is estimated to be $1.3x10^{11}$ m^2, or 2% of global inundated wetlands.

Non-forested Swamps. Non-forested swamps are peat-poor, inundated grasslands covering an area of $1.3x10^{11}$ m^2, or 2% of global inundated wetlands. They tend to emit about as much methane as forested swamps.

Alluvial Formations. Alluvial formations are the smallest methane producers of the temperate systems. In the temperate zone, alluvial formations are usually cold-deciduous, alluvial forests. The area is estimated to be $0.4x10^{11}$ m^2, or less than 1% of global inundated wetlands.

2.1.3 Northern Wetlands

A number of factors distinguish different ecosystems in the northern wetlands. These factors include soil moisture and the presence of winter emissions. To address these factors, northern wetlands are generally divided into arctic (above 60°N) and boreal (45°-60°N) wetlands. Since soil moisture is a major factor controlling methane emissions, arctic and boreal wetlands are further subdivided into "flooded," "well-drained," and "mixed" (both flooded and well-drained soils) moisture classes. Well-drained wetlands are areas where the water table is below the surface, and there is no standing water at the soil surface. Finally, at several sites both in the arctic and boreal regions, small lakes and ponds appear to contribute significantly to emissions.

[14] This difference in emission rates is based on a limited sample size and may not be statistically significant; see section 2.2.2

Given these factors, northern wetlands may be divided into eight categories:

ARCTIC WETLANDS	BOREAL WETLANDS
flooded	**flooded**
well-drained	well-drained
mixed	mixed
lakes	lakes

The major emission differences between these ecosystems are (1) flooded wetlands have significantly higher emissions than well-drained ones, with mixed wetlands falling somewhere in between; (2) lakes appear to be significant sources of methane, but the data set is very limited; and (3) winter emissions are believed to be higher in the boreal region, although there is little data. Arctic and boreal latitudes appear to have similar emission rates at other times.

Data on areal extent is not specifically available for all eight of these wetland types. Therefore, the following three categories (shown in bold on the table above) are used to represent all northern wetlands: (1) flooded arctic wetlands, (2) flooded boreal wetlands, and (3) well-drained arctic wetlands. These three systems are believed to represent the vast majority of northern wetland areas, and therefore, the global emissions results should not suffer significantly from the use of these three systems to represent all northern wetlands. However, more accurate estimates of northern wetland emissions can be made in the future if the specific area of all eight types is defined.

Flooded Arctic Wetlands. In the arctic, wetlands vegetation is limited primarily to grasses, sedges, and low shrubs. Since these wetlands are generally not associated with rivers, small variations in microtopography commonly create differences in inundation and vegetation.[15] Inundated wetlands in the arctic are estimated to cover 14.7×10^{11} m^2, which is 50% of northern wetlands and 28% of global inundated wetlands (Matthews and Fung 1987).[16]

Flooded Boreal Wetlands. Moving south from the arctic into the boreal region, trees become more common and wetlands become more diverse. Common wetlands in the boreal zones include bogs and fens. Bogs are peat-producing wetlands that are characterized by their isolation from surface-water sources. They receive water and nutrients only from rainfall, a condition termed ombrotrophy. These wetlands are quite acidic and poor in nutrients, and vegetated by plants adapted to these rigorous conditions. Fens, on the other hand, are commonly in contact with surface waters

[15] On a small scale, the floodplain of a river is generally a homogeneous system in terms of topography, inundation and vegetation. However, non-riverine systems -- which are not smoothed by the action of a river -- can exhibit uneven topography leading to flooded and non-flooded areas in close proximity.

[16] In deriving this area, Matthews and Fung (1987) included areas that are referred to above as mixed arctic and arctic lakes.

(minerotrophy) and are more alkaline, have higher nutrient levels, and have more diverse vegetation. The area of flooded boreal wetlands is estimated at 15×10^{11} m^2, comprising 50% of northern wetlands and 28% of global inundated wetlands (Matthews and Fung 1987).[17]

Well-drained Arctic. These wetlands (also called dry tundra) are characterized by treeless, vegetated plains and a water table that is generally below but near the soil surface. Dry tundra area covers an estimated 58.7×10^{11} m^2, which is larger than the entire area of global inundated wetlands. (This number is derived by subtracting the area of high latitude inundated wetlands (Matthews and Fung 1987) from the total area of tundra (Matthews 1983).)

2.2 Review of Emission Measurements

This section provides a state-of-the-art review of methane emission measurements. Using the classifications developed above, this section also provides an estimate of the average methane emission rate from each of the major wetland types.

During the past decade, the number of studies on methane production and release from wetland environments has increased substantially, especially in North America, making it possible to develop more reliable average emission rates for the major wetland types. Since methane emissions can vary by orders of magnitude in relatively small time- and space-scales, extrapolating emissions from flux measurements can be an uncertain process. This characteristic variability in fluxes also increases the difficulty in making cross-study and cross-ecosystem comparisons as these depend on the degree to which measurement sites are representative of larger systems. It is therefore encouraging to note that there is reasonable agreement in the results of the various measurement programs to date. Moreover, these measurement programs include a variety of measurement techniques spanning spatial scales from less than 1 m^2 to hundreds of km^2 (Fan et al. 1992; Bartlett et al. 1992; Ritter et al. 1992; Roulet, pers. comm.).

2.2.1 Tropical Measurements

Emission measurements from the tropics are generally high in comparison with those from the temperate and northern regions. They are also variable, which is probably a consequence of CH_4 release by bubbling, as reported in various studies (Bartlett et al. 1988; Crill et al. 1988; Bartlett et al. 1990; Devol et al. 1990; Keller 1990). Ebullition, or bubbling, is one of three pathways by which methane can escape from wetlands to the atmosphere. Since bubble release is sporadic and can emit large amounts of gas, measurements taken with and without bubbling are dramatically different.

Tropical emission measurements have been made at several sites in the Amazon, and sites in the Orinoco river flood plain in South America, Panama, and the Congo river basin in Africa (see Exhibit 2-1). The CH_4 flux data from these sources is summarized in Appendix B. All of the data included in Appendix B have been published in the last four years.

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[17] In deriving this area, Matthews and Fung (1987) included areas that are referred to in this report as mixed boreal and boreal lakes.

Exhibit 2-1 Measurements in Tropical Regions Summarized in this Report	
Tropical Site	**References**
Amazon	Devol et al. 1988 Bartlett et al. 1988 Bartlett et al. 1990 Devol et al. 1990 Wassmann et al. 1992
Orinoco	Smith and Lewis 1992
Panama	Keller 1990
Congo	Tathy et al. 1992

The tropical emission measurement data from Appendix B can be aggregated into the three wetland types defined for the tropics (open water, non-forested swamps, and flooded forests; see Exhibit 2-2) with the following results:

Non-forested Swamps. Emissions from non-forested swamps are generally higher than the emissions from other tropical systems and cover a wide range. In the Amazon, average fluxes from non-forested swamp systems range from 131 to 390 mg CH_4/m^{2}/d, with most values at about 200 mg $CH_4/m^2/d$. Data from the Orinoco River appear to be an order of magnitude lower (30 mg $CH_4/m^2/d$), suggesting that there may be significant differences between the two systems.

Flooded Forests. Emissions from flooded forests tend to be somewhat lower than those from non-forested swamps but also cover a wide range, from 7 to 230 mg $CH_4/m^2/d$ in the Amazon. Values from inundated African forests may be somewhat lower than those from the Orinoco (106 and 174-307 mg $CH_4/m^2/d$, respectively), while those from a site in Panama appear to be somewhat greater (346 mg $CH_4/m^2/d$).

Open water. Open-water sites generally have lower emissions than sites with vegetation (floating macrophytes (mats) and flooded forests). In the Amazon, average methane fluxes from open water span a relatively narrow range, from 27 to 88 mg $CH_4/m^2/d$. Open water flux measurements from Panama cover a broader range, from 54 to 967 mg $CH_4/m^2/d$. However, since most of the Amazonian open-water sites studied were in water depths similar to the deeper water Panamanian sites (greater than 5 meters) with lower emissions, these data sets may actually be consistent. High-water data from seven lakes on the Orinoco River flood plain are somewhat lower (an average of 7.5 mg $CH_4/m^2/d$) but are consistent with the Amazonian data.

In order to calculate average emission rates from the database of tropical measurements, a weighted average of high-water and low-water measurements is calculated in order to account for annual variability. This high-low average emission rate is then averaged with those measurements from sites observed year-round (see Exhibit 2-2).

Exhibit 2-2

Average Emission Rates from Tropical Wetlands
(Derived from Appendix B)

HABITAT	AVERAGE EMISSION RATE (mg $CH_4/m^2/d$)
Non-forested Swamps	233
Flooded Forest	165
Open Water	148

2.2.2 Temperate Measurements

All of the data collected in this climatic region are from wetland sites in the United States. In general, the data fall into two broad vegetation types: forested swamps and non-forested swamps (both saline and freshwater). These vegetation types correspond to the dominant types of U.S. wetland areas. Appendix C presents CH_4 emission data from wetlands in the temperate to subtropic zones, roughly from 45° to 25° N.

The observed emission rates range widely, from isolated negative fluxes (consumption of atmospheric CH_4) to emissions more than three orders of magnitude higher: -7.9 to 3,563 mg $CH_4/m^2/d$. Emission rates for the different ecosystems are:

Forested Bogs. Emission rates for forested bogs appear to be the highest for temperate systems, although the number of emission measurements is limited. The available measurements were averaged to derive a mean temperate bog flux of 135 mg $CH_4/m^2/d$ (number of sites, *n*, = 5) (Yavitt et al. 1990; Crill, unpublished data).

Forested and Non-forested Swamps. These systems appear to have emission rates about half as large as forested bogs. An average emission rate for temperate forested swamps was calculated to be 75 mg $CH_4/m^2/d$ ($n = 18$), and for non-forested swamps, 70 mg $CH_4/m^2/d$ ($n = 25$) (see Appendix C).

Alluvial Formations. Emissions from alluvial formations were estimated from brackish and fresh open water (DeLaune et al. 1983; Appendix C); lakes in the Okefenokee Swamp (Bartlett, unpublished data); and flood plain cypress swamps (Harriss and Sebacher 1981). The emissions average 48 mg $CH_4/m^2/d$.

2.2.3 Northern Measurements

Measurements from the northern wetlands span more than three orders of magnitude, from less than 1 to roughly 1,940 mg $CH_4/m^2/d$, and include a wide variety of vegetation, moisture, and soil types. A single flux of 12,068 mg $CH_4/m^2/d$, roughly an order of magnitude greater than all others at this site, is reported from an Alberta beaver pond. Appendices D, E, and F list reported flux measurements from northern wetlands, covering a latitudinal range of 45° to 70°N. These measurements may be divided between arctic and boreal measurements as described below.

Arctic Measurements

Measurements in subarctic and arctic tundra (above 60° N) are mainly from three regions in Alaska:

- Fairbanks, in the interior of the state, where the only annual, multi-year measurements have been made (Whalen and Reeburgh 1988; Whalen and Reeburgh, in press).
- The coastal plain on the North Slope, where at least four separate investigators have made measurements encompassing both large and small spatial scales (Sebacher et al. 1986; King et al. 1989; Whalen and Reeburgh 1990a; Morrissey and Livingston 1992).
- Coastal tundra on the delta of the Yukon and Kuskokwim Rivers, where investigators have made measurements on a variety of scales using an array of measurement techniques, including tower and aircraft measurement, during the NASA Arctic Boundary Layer Expedition (ABLE 3A) (Bartlett et al. 1992; Fan et al. 1992; Ritter et al. 1992).

Within each of these three regions, the agreement in methane flux data was fairly good among measurements in similar habitats (e.g., North Slope region: Sebacher's wet coastal tundra had average emissions of 119 mg $CH_4/m^2/d$; Whalen & Reeburgh's wet tundra had average emissions of 90 mg $CH_4/m^2/d$; Livingston & Morrissey's meadow tundra had average emissions of 64.4 mg $CH_4/m^2/d$; wet tundra = 100 mg $CH_4/m^2/d$; very wet tundra = 254 mg $CH_4/m^2/d$). Agreement also appears fairly good among these three regions.

The only arctic flux measurements not from Alaska were made at a series of sites in a Swedish mire, ranging from drier raised areas (ombrotrophic) to wetter depressions (minerotrophic) (Appendix D). The average fluxes from hummocks and higher areas in Sweden are quite similar to those from comparable Alaskan sites. The average flux from wetter sites in Sweden (360 mg $CH_4/m^2/d$) was higher than emissions from wet Alaskan sites, but this result was largely driven by high measurements on a single date.

Boreal Measurements

In the boreal zone (roughly 45°-60° N), measurement sites fall primarily into two areas:

- Northern Minnesota (in and around the Marcell Forest and the Red Lake Peatland),

- Southeastern/southern Canada (Schefferville area and the Hudson Bay Lowlands). Small- and large-scale measurement techniques were used in this area. For example, in 1990, an integrated flux measurement campaign involving chamber enclosure (small-scale) measurements, and eddy correlation flux (large-scale) measurements taken from a micrometeorological tower and from several aircraft was conducted in the Schefferville Canada area (NASA's ABLE 3B/Canadian NOWES).

Emissions from more western sites in Alberta, Canada have also been recently examined (Vitt et al. 1990).

A comparison of measurements within one boreal region, made at different times by a variety of investigators suggests that although there may be significant spatial and temporal variability, average measurements generally agree, in part because flux measurements have relatively high variance. In Marcell Forest, for example, standard errors range from 3% to 35% of means (Harriss et al. 1985; Crill et al. 1988; Dise, submitted (a)). However, significant differences appear to exist between the two major regions, northern Minnesota and southeastern/southern Canada. It is currently unclear why these regional differences occur, but they suggest the difficulty in extrapolating flux measurements to other regions, even those with similar vegetation and climate regimes.

In summary, average emissions from flooded arctic soils (96 mg $CH_4/m^2/d$) appear to be approximately equal to those from flooded boreal regions (87 mg $CH_4/m^2/d$). However, differences within the boreal sites measured complicate this conclusion, and emissions during winter months in the boreal zone may be higher. Well-drained tundra soils in the arctic most frequently appear to be small sources, 0.6-11 mg $CH_4/m^2/d$, with sporadically occurring negative fluxes (consumption of atmospheric methane) generally between -0.5 and -3 mg $CH_4/m^2/d$ (Whalen and Reeburgh 1990a; 1990b; Fan et al. 1992; Bartlett et al. 1992; King et al. 1989). The average flux from well-drained arctic tundra is 7 mg $CH_4/m^2/d$.

Emission data available for northern wetlands are summarized in Exhibit 2-3. Sufficient data were available to derive average emission rates from almost all eight of the unique northern systems. However, it is currently possible to measure the areal extent of only three of these systems: flooded arctic, flooded boreal, and well-drained arctic. Therefore, global emissions are calculated using the average emission rates from these three systems (shown in bold face). The area used to represent flooded boreal wetlands is assumed to include the areas of mixed boreal and boreal lakes. Similarly, flooded arctic includes mixed arctic and arctic lakes. Thus, the only area that may not be accounted for is well-drained boreal, which is probably insignificant in terms of global emissions (Patrick Crill, pers. comm. 1992).

Exhibit 2-3

Average Emission Rates from Northern Wetlands
(Derived from Appendix D; Flux units: mg $CH_4/m^2/day$)

Moisture Class	Region	Avg. Flux	Std. Error of Mean	Number of Studies	Range
Flooded	**Arctic**	96	21	28	2.8 - 360
	Boreal	87	18	49	0 - 664
Well-drained	**Arctic**	7	2.0	14	0.6 - 29
	Boreal	10	2.7	5	3.3 - 21
Mixed[1]	Arctic	21	9.6	3	1.6 - 31
	Boreal	-	-	0	-
Lakes	Arctic	51	16	6	3.8 - 112
	Boreal	172	75	8	12 - 518

[1]Includes a mixture of flooded and well-drained soils within the vegetation grouping.

2.3 Global Emissions

Global annual methane emissions from natural wetlands is the sum of the emissions from the individual ecosystems. To calculate these emissions, it is necessary to know the area of the ecosystem, its average daily emission rate, and the active period of emissions over the course of a year. With this information, the following equation can be used to estimate the contribution to global emissions from a particular wetlands system (Matthews and Fung 1987; Aselmann and Crutzen 1989):

$$\text{Annual Emissions} = \text{Area} \times \text{Emission Rate} \times \text{Emission Period}$$

where annual emissions is Tg CH_4/yr, area is m^2, emission rate is mg CH_4/m^2/day, and period is days/year.

2.3.1 Global Tropical Emissions

Globally, tropical wetlands are estimated to emit about 66 Tg of methane annually. Non-forested swamp wetlands contribute 34 Tg CH_4/yr; flooded forest wetlands contribute 31 Tg/yr; and open water wetlands contribute 2 Tg/yr. These annual estimates are based on the information summarized in Exhibit 2-4. The average emission period in the tropical region is estimated to be 180 days/year because this is roughly the length of the annual wet season (Matthews and Fung 1987).

Exhibit 2-4

Global Tropical Methane Emissions

Ecosystem	Emission Rate ($mg\ CH_4/m^2/d$)	Area ($10^{11}m^2$)	Emission Period (days)	Annual Emissions (Tg/yr)
Non-For. Swamps	233	7.9	180	34
Flooded Forests	165	10.4	180	31
Open Water	148	0.5	180	1.7
TOTAL		19	180	66

The methane emission estimate of 66 Tg/year from tropical wetlands is significantly higher than estimates derived by other researchers. This difference is due to the use of the current database of measurements, which indicates that the average emission rates from this region are considerably higher than previously believed. Using a substantially smaller data base than was available for the present analysis, Matthews and Fung (1987) calculated that tropical wetlands contribute 28 Tg CH_4/year. Using different data sources for wetland areas, emission season assumptions, and a data base on fluxes that was larger than the one used by Matthews and Fung but smaller than the current data base, Aselmann and Crutzen (1989) estimated that tropical wetlands release about 42 Tg/yr.

2.3.2 Global Temperate Emissions

Temperate wetlands are estimated to release 5 Tg CH_4/yr. This annual estimate is based on the emission rates, area and emission periods listed in Exhibit 2-5. Annual changes in both temperature and inundation determine the emission period in the temperate zone, where seasonal as well as permanent wetlands are present. On average, the emission period is estimated to last for 150 days each year, with the exception of those wetlands between 30° N and 20° N, where it is estimated to last for 180 days. This period corresponds roughly to the annual period of warm temperatures.

2.3.3 Global Northern Emissions

Total emissions for flooded soils in the arctic and boreal regions are calculated to be 14.1 Tg/yr and 19.5 Tg/yr, respectively. A global flux of 4 Tg/yr is calculated from dry (well-drained) tundra. The total northern wetlands contribution to global emissions is therefore 38 Tg/yr. These annual estimates are based on the information listed in Exhibit 2-6.

In these extreme environments, temperature is the primary factor creating seasonality. The assumed emission periods are 100 days for areas above 60° N latitude and 150 days for areas between 45° N and 60° N. These periods correspond roughly to the annual thaw season, as winter fluxes are assumed to be zero.

Exhibit 2-5

Global Temperate Methane Emissions

Ecosystem	Emission Rate (mg $CH_4/m^2/d$)	Area ($10^{11}m^2$)	Emission Period[1] (days)	Annual Emissions (Tg/yr)
Forested Bogs	135	1.0	150, 180	2.1
Forested Swamps	75	1.3	150, 180	1.6
Non-forested Swamps	70	1.3	150, 180	1.5
Alluvial Formations	48	0.4	150, 180	0.3
TOTAL		4.1	150, 180	5.4

[1] Temperate emissions are calculated using a period of 150 days, except for temperate wetlands between 20° N and 30° N, for which a period of 180 days is used.

Exhibit 2-6

Global Northern Methane Emissions

Ecosystem	Emission Rate (mg $CH_4/m^2/d$)	Area ($10^{11}m^2$)	Emission Period (days)	Annual Emissions (Tg/yr)
Boreal (Flooded)	87	15.0	150	20
Arctic (Flooded)	96	14.7	100	14
Arctic Tundra (Well-drained)	7	58.7	100	4
TOTAL		88.4		38

This estimate for the northern contribution to global emissions is somewhat smaller than earlier estimates for this region. In 1987, based largely on northern emissions from Sebacher et al. (1986), Matthews and Fung (1987) estimated that northern wetlands (50°-70° N) made a major contribution to atmospheric methane, calculating an annual flux of 62 Tg, or roughly 60% of the total emissions from all wetlands. A recent recalculation of the global contribution from wetland ecosystems (Bartlett et al. 1990) based on the Matthews and Fung wetland areas and model but using a larger flux data base, suggested that global emissions from northern high-latitude areas may be lower than those estimated by Matthews and Fung, but still roughly 39 Tg/yr. Aselmann and Crutzen (1989) also found that northern emissions are somewhat lower than first thought and estimated that the region releases about 24 Tg/yr. Based on their data from Fairbanks, Whalen and Reeburgh calculated global emissions from areas north of 50° N ranging from 28 to 102 Tg/yr. If uncertainty in vegetation cover types is included, the range in emissions encompasses nearly one order of magnitude 13.7 to 134.5 Tg/yr (Whalen and Reeburgh 1992).

2.3.4 Summary of Global Emissions from Wetlands

The contribution of methane emissions from all wetlands is 109 Tg (see Exhibit 2-7). Of this total emissions, 60% comes from tropical wetlands. While tropical wetlands account for a considerably smaller area than northern wetlands, their emission rates are substantially higher and they are active for a longer period each year. Temperate wetlands have emission rates of approximately the same magnitude as inundated northern systems, and longer emission periods, but the areal extent is small enough that they account for only 5% of global wetland emissions. Northern wetlands (including dry tundra) account for the majority of global wetland area, but given the very low emission rate of dry tundra, northern wetlands account for only 35% of total wetland emissions.

While the regional totals calculated here are somewhat different from other studies, the overall total is similar to other global emission estimates. These totals have ranged from 80 to 115 Tg/yr in recent studies (see Exhibit 2-8).

2.4 Effects of Environmental Variables

To investigate future methane emissions from wetlands, it is necessary to understand the factors that control methane production and release from different wetland ecosystems. This section discusses what is currently known about the major environmental variables that influence methane emissions in these different systems. This section also presents the results of a 1992 workshop held to discuss these environmental variables and the rankings that were developed in the workshop to characterize the importance of the variables in the different systems.[18]

Methane fluxes from natural wetlands have been linked to a wide array of environmental variables. However, not all of these variables are expected to be altered significantly by climate change. Therefore, the following discussion will focus on environmental variables that could play a major role in influencing future emissions. Furthermore, because the temperate zone makes a small contribution to global wetland emissions compared to other regions, discussion is concentrated on the tropical and northern zones.

To investigate the effect of changing climate, it is necessary to examine the potential effect of the important environmental variables on the emission rate itself, the wetland area and the emission period. Separating variables into those affecting the emission rate as

[18] A workshop on variables controlling future methane emissions from wetlands was held at the University of New Hampshire on March 10 and 11 1992 through a grant by EPA's Office of Air and Radiation. The workshop brought together experts in fields related to trace gas emissions from natural systems. Workshop participants are listed in Appendix A.

Exhibit 2-7

Global Annual Methane Emissions from Natural Wetlands

Ecosystem	Emission Rate (mg CH_4/m²/d)	Area ($x10^{11}m^2$)	Emission Period (days/yr)	Annual Emissions (Tg CH_4/yr)
Tropical Wetlands		19		66
Non-Forest Swamps	233	7.9	180	34
Flooded Forests	165	10.4	180	31
Open Water	148	0.5	180	1.7
Temperate		4.1		5
Forested Swamps	75	1.3	150, 180[1]	1.6
Non-Forest Swamps	70	1.3	150, 180	1.5
Alluvial Formation	48	0.4	150, 180	0.3
Forested Bogs	135	1.0	150, 180	2.1
Northern Wetlands		88.4		38
Boreal	87	15.0	150	20
Arctic	96	14.7	100	14
Well-drained Tundra	7	58.7	100	4
Total Wetlands		111		109

[1] Temperate emissions are calculated using a period of 150 days, except for temperate wetlands between 20° N and 30° N, for which a period of 180 days is used.

opposed to wetland area or emission period can be a difficult and somewhat arbitrary task because these parameters are highly interrelated. However, some generalizations can be made about the most important environmental variables.

Variables Affecting Emission Rate

- Precipitation as it affects water level.
- Plant community as characterized by net primary productivity, primary mode of methane transport, and nutrient availability.
- Temperature.

Exhibit 2-8

Comparison of Global Emissions Studies

Study	Climate Zone: Northern (above 50°N)	Climate Zone: Temperate (20-50°N; 30-50°S)	Climate Zone: Tropical (20°N-30°S)	Global Estimate (Tg/yr)
Matthews & Fung 1987	65	14	32	111
Aselmann & Crutzen 1989	25	12	43	80
Bartlett et al. 1990	39	17	55	111
Fung et al. 1991	35†		80‡	115
This report*	34	5	66	105

† Bogs and tundra (Fung et al. classified wetlands not by latitude but by four ecosystems. However, bogs and tundra exist almost exclusively in the north, while swamps and alluvial formations are found almost only in the tropics.)

‡ Swamps and alluvial formations

*Northern wetlands are defined in this report as those wetlands at or above 45°N; well-*drained tundra not included in this comparison because it was not included in any of the other* studies.

Variables Affecting Wetland Area and Emission Period

- Precipitation
- Temperature
- Actual Evapotranspiration
- Human impacts
- Sea level change
- Permafrost

A discussion of these variables follows.

2.4.1 Emission Rate

To characterize the importance of the environmental variables that could influence changes in methane emission fluxes, workshop participants developed rankings of the importance of the different environmental variables for major wetland ecosystems (see Exhibit 2-9). For this exercise, the northern and tropical ecosystems were divided into somewhat different subgroups than those used to estimate current emissions (listed above). Northern and tropical wetlands were divided into forested, non-forested, and open water systems. In addition, non-forested ecosystems were sub-divided into graminoid (grassy) and bryophyte (mossy) dominated wetlands. These subgroups preserve important information on available nutrient levels, plant productivity, and plant ability to transport gas.

2.4.1.1 Precipitation or Water Level

In those regions where precipitation is expected to increase due to climate change, methane emissions are also expected to increase. This is because the availability of water is the primary condition which must be fulfilled to have a wetland (Harriss et al. 1982). Once a soil is wet, other environmental variables such as temperature are important in determining the rate at which soil CH_4 is produced and released. In addition to being a prerequisite for methane generation, the water level of a wetland has also been correlated with the emission rate (Harriss et al. 1988; Bartlett et al. 1989). As illustrated in Exhibit 2-9, the significance of water level of a wetland can be divided into three aspects:

Timing and Duration of Saturation. Changes in precipitation could alter the timing and duration of saturation of wetlands. This timing is important in all ecosystems except open-water systems, which are permanently inundated. For example, the average emission rate will decrease if the saturation period shifts from warmer to colder months or decreases in length.

Flushing Rate. Increases in precipitation could also act to increase the flushing rates of systems. In general, higher flushing rates result in lower fluxes. This aspect is important to alluvial systems, which currently have lower emission rates than other wetlands for this reason.

Water Table Depth. Increases in precipitation could increase the depth of the water table in all wetland areas. This effect could result in higher methane fluxes, since the depth of the water table has been positively correlated with methane fluxes in some regions.

Information is available that describes the effects of changes in water level on methane fluxes. In northern wetlands, several researchers have determined statistical relationships. For example, Dise (1991) relates water level, seasonal soil temperature, and methane flux for a series of bogs and fens that cover a gradient in wetness in northern Minnesota. The water table explained 62% of the variability in the methane flux. Ninety percent of the annual variability was accounted for when annual soil temperature was added to the regression equation. An additional variable that explains some of the residual uncertainty in this model is the Von Post peat humification index of the sites, a measure of the degree of decomposition. An earlier effort by Svensson (1976) also reports a quantitative relationship between methane flux and soil moisture (as % dry weight). Furthermore, Moore et al. (1990) found that although flux was poorly correlated with water table and temperature at any one of their sites, examination of the entire data set indicated a relationship between these variables and flux.

The relationship between water level and methane flux is more difficult to discern in the tropics. This difficulty arises largely from the high variability in tropical emission rates. While emission measurements taken during low water generally appear to be lower than those collected during higher water levels, it is not currently clear if they are statistically different. For example, the seasonal data set (averaged over the entire season) from lakes sampled

Exhibit 2-9

Effects of Environmental Variables on CH_4 Emission Rate

Rankings are relative and refer to within ecosystems (columns), not across ecosystems (rows).
(1 = not important; 5 = very important; NA = not applicable)

VARIABLE	Aspect	NORTHERN				TROPICAL		
		Forested	Non-For. (grassy)	Non-For. (mossy)	Open water	Forested	Non-For.	Open Water
Water Level	timing & duration of saturation	5	5	5	NA	5	5	NA
	flushing rate	5	5	5	5	5	5	5
	water table depth	5	5	5	5	5	5	5
Net Plant Productivity	carbon uptake & root releases	5	5	3	3	5	5	3
	litter quality & carbon storage	5	5	5	3	1	1	2
Exchange Mechanism	plant transport	3	5	1	5	1	1	3
	diffusion	5	3	5	1	3	3	1
	bubbling	1	1	1	5	5	5	5
Nutrients		5	5	5	5	1	1	1
Temperature	length of thaw	5	5	5	5	NA	NA	NA
	active season temp.	5	5	5	5	3	3	3

around Manaus is indistinguishable from most of the data collected over shorter time periods (Devol et al. 1990). In more permanently inundated wetlands in Panama, wet season fluxes ranged from 40% to nearly an order of magnitude greater than those during the dry season, but were usually not statistically different due to high variability (standard errors averaged 76% of the mean in the dry season and 32% in the wet season) (Keller 1990).

2.4.1.2 Temperature

Increases in soil temperature are likely to have the greatest influence on methane fluxes for systems with sufficient moisture available. Two important aspects of soil temperature are:

- Length of the thaw period.
- Temperature of the season in which most of the methane is emitted (the active season).

For northern wetlands, both the length of the thaw period and the temperature of the active season can be expected to increase as atmospheric temperatures increase. Methane fluxes would be expected to increase, in turn, as a growing body of information indicates that there is a positive relationship between methane flux and these factors. For example, laboratory experiments have demonstrated that methane flux increases exponentially with temperature (Koyama 1963; Moore et al. 1990; Crill, pers. comm.). Based on both laboratory and field data, several exponential relationships have been postulated, including the following formula from Fung et al. (1991):

$$flux(t) = flux(t_o) * Q_{10}^{(T-To)/10}$$

where

T = temperature,
t = time, and
Q_{10} = 2 (a constant coefficient; roughly equals the factor by which emissions will increase for a 10°C increase in temperature).

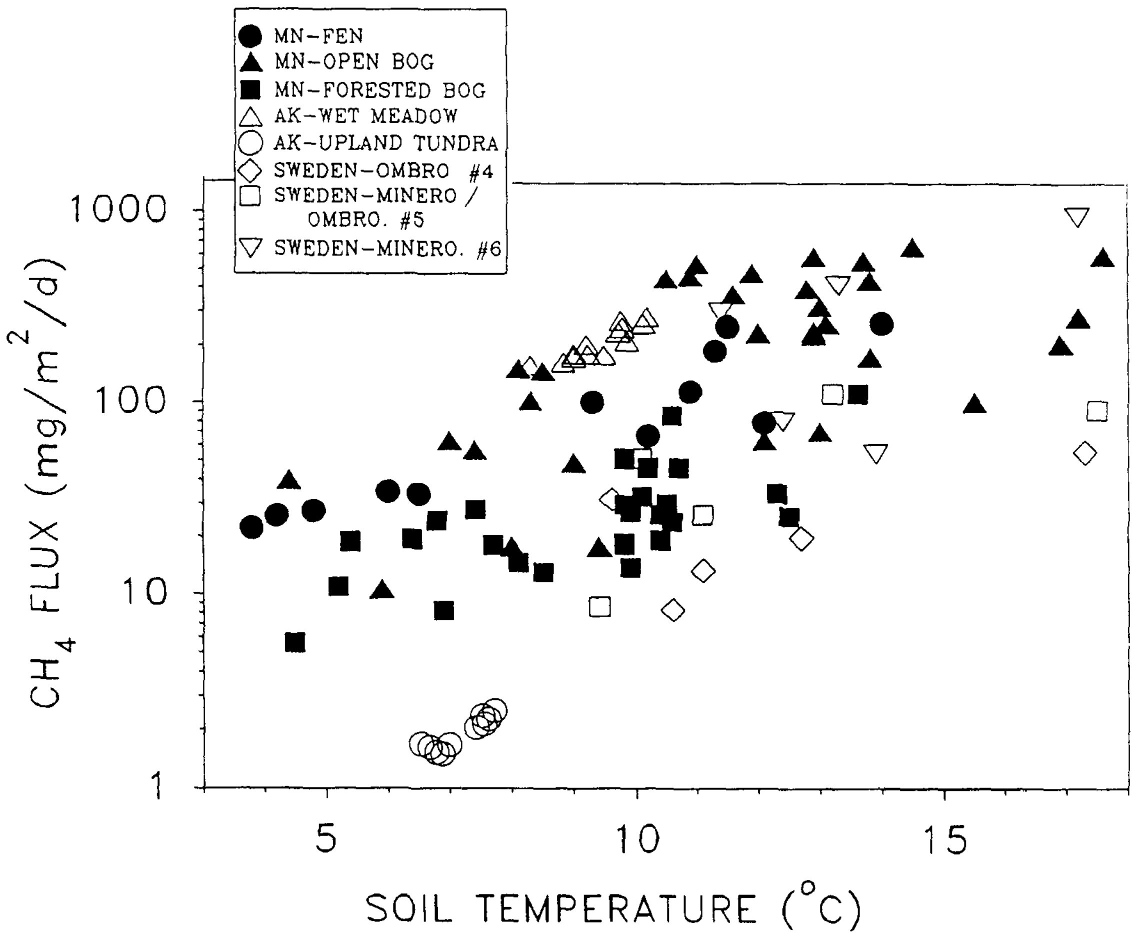
The value of 2 for Q_{10} is based on observational data from northern wetlands which would imply a Q_{10} value greater than 2. However, these data have been adjusted to account for the effects on emissions from changes in hydrology and substrate quality (Fung et al. 1991).

The active season temperature has been recently correlated with emissions from several northern habitat types, including wetlands in Minnesota, Alaska, and Sweden (see Exhibit 2-10). A regression of this newly available data (Exhibit 2-11) shows that despite considerable variability within each data set, the data tend to fall along a similar line. This similarity is true for habitats within a single region and across arctic and boreal zones and may imply a functional relationship between temperature and methane release across a variety of high-latitude environments. However, the similarity could also be a function of a limited data base.

The data in Exhibits 2-10 and 2-11 imply an average Q_{10} value of about 8 (range 5 to 50), which is a more pronounced temperature effect than postulated by Fung et. al. (1991) (see above). However, like the data used in Fung et al. (1991), there is reason to believe that the emission increases observed in these studies are influenced by factors other than

Exhibit 2-10

Emissions Rate vs Soil Temperature in Northern Wetlands



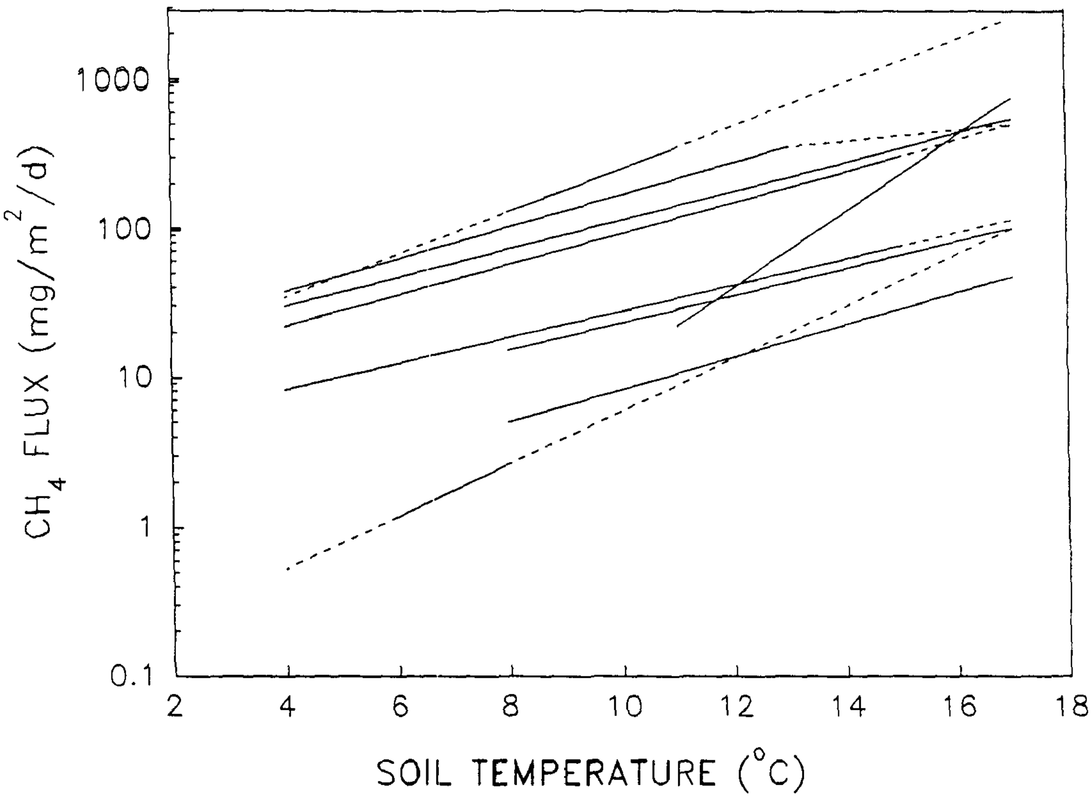
Sources: Svensson and Rosswall (1984); Crill et al. (1992); Bartlett et al. (1992); Livingston and Morrissey (1992).

temperature (e.g. moisture and organic matter availability), and therefore the Q_{10} values may be artificially high. High field related Q_{10} values may also result from a natural seasonal increase in methanogenic bacteria. Because many of the northern latitude environments are initially frozen sediments and methane emission rates at the onset of the experimental season are very low values, it is probable that significant increases in the methanogenic population size occur over the course of the experimental season (Lee Mulkey pers. comm. 1993).

It is more difficult to assess the effects of increased temperatures on tropical wetlands. Temperatures vary annually by only a few degrees in the tropics, and tropical emission measurements are intrinsically highly variable, making it difficult to distinguish correlations between the active season temperature and methane fluxes.

Exhibit 2-11

Regression of Emission Rate Data in Exhibit 2-10



2.4.1.3 Plant Community

Plant populations can be modified as a result of climate change. These modifications can result from changes in temperatures, or precipitation, or from enhanced CO_2 concentrations. Modifications in plant populations can be expected to affect methane emission rates, since plants have a variety of complex effects on both total emissions of methane and the mechanisms by which methane is released. Some key characteristics of plant communities relevant to methane emissions include net primary productivity (NPP), nutrients, and exchange mechanisms (ways that CH_4 is transported from areas where it is produced to the atmosphere) (see Exhibit 2-9) (Whiting et al. 1991; Schutz et al. 1991; Chanton and Dacey 1991). The ways in which these plant characteristics affect methane emissions are discussed below.

Net Primary Productivity. Plants serve as the sources of organic substrate for the decomposition process that leads to methane emissions from wetlands. One measure of the availability of substrate is the net primary productivity (NPP). NPP is the gross amount of carbon fixed by plants minus the carbon consumed for plant maintenance.

This productivity is manifested in biomass production and root releases. Plant productivity is itself controlled by other environmental variables, including temperature, precipitation, and atmospheric concentrations of carbon dioxide and ozone. Thus, methane emissions from wetlands will be indirectly affected by climate change through its effect on plant productivity.

With the exception of open water areas, where few rooted plants exist and organic sources are either advected in or fall through the water column, NPP is critical to methane emission rates. NPP can affect methane production in two ways:

> *Carbon Uptake and Root Releases.* The terms carbon uptake and root releases refer to the carbon that is released from plants and is easily and quickly (i.e., within a season) decomposed. For example, non-forested swamps in the tropics have higher emission rates than flooded forests in part because carbon from graminoid (grassy) plants is more easily decomposed than from woody plants. Wetlands release more methane during the times of year when plants are releasing more carbon (Wilson et al. 1989).
>
> *Litter Quality and Carbon Storage.* The terms litter quality and carbon storage refer to the quantity and quality of the carbon from plants that is dropped onto the soil surface, and that therefore, may be stored for several seasons on the soil surface or within the soil. In the tropics, where generally little peat accumulates, litter quality is probably relatively unimportant (Exhibit 2-9).

Exchange Mechanisms. There are three exchange mechanisms by which methane produced in the soil layer can be transported to the atmosphere: plant transport, molecular diffusion through soil and water, and bubbling. Plant transport and bubbling are much faster mechanisms than molecular diffusion, and the degree to which these two mechanisms are available largely determines how much of the methane will reach the atmosphere and how much will be oxidized. The predominance of one mechanism varies with latitude and habitat (Exhibit 2-9), and could change as a changing climate alters the plant community.

> *Bubbling.* Bubbling is frequently the most significant pathway for CH_4 loss to the atmosphere in many habitats, except for vegetated northern wetlands, where it has seldom been observed. In the Amazon, for example, direct measurements of bubble emissions determined that bubbles contributed from 20% to 80% of total emissions, with lower percentages from areas of open water and higher figures from mats of floating grasses (Bartlett et al. 1988; Crill et al. 1988; Bartlett et al. 1990; Devol et al. 1990). It is not known, at this point, if the occurrence of bubbling in an area merely affects the timing of methane release or if it can alter the magnitude of the annual emission. The environmental controls on bubbling are also not well understood, but it is possible that climate change could increase or decrease the magnitude or areal extent of bubbling, and therefore affect global methane emissions.
>
> *Diffusion.* This mechanism is universally available and is the most important one in those ecosystems where the other two mechanisms are not available or

not particularly functional, such as well-drained tundra. However, diffusion is not likely to change significantly with future climate change.

Plant Transport. The ability of plants to act as gas conduits to the atmosphere varies significantly with species and plant structure, so the relative importance of this loss mechanism can be highly site-specific and highly dependent on the plant community (Sebacher et al. 1985; Chanton and Dacey 1991; Chanton et al. 1992). This is true, for example, in vegetated northern wetlands, where bryophyte plants (mosses) have no root structures and thus do not take up and release CH_4. Alternatively, graminoid (grassy) plant species and aquatic vegetation in open water areas are more effective as conduits for release than are the woody structures of trees and shrubs. Therefore, if climate change affects plant productivity or species mix, global emissions could be significantly altered.

Nutrients. Nutrient levels are generally of secondary importance because they help determine the plant species in an area, which in turn determine NPP and exchange mechanisms. While there are usually sufficient nutrients in the tropical regions to support the existing plant communities, many northern wetland systems are highly ombrotrophic (fed by rainfall, not ground water) and poor in nutrients. This nutrient deficiency could limit changes in plant communities in these regions since species requiring high nutrient levels would be unable to enter the region. Alternatively, species adapted to low nutrients could become established.

2.4.2 Wetland Area and Emission Period

Variations in climate are likely to result in changes in both the areal extent of wetlands and in their annual active period of emissions. Exhibit 2-12 provides an assessment of the relative importance of potential changes in the environmental variables controlling the area and emission period of wetlands. The relative effects of environmental variables are the same for most northern and tropical wetlands.[19] Although technically not a natural environmental variable, human impacts are included here because they could be a very large determining factor in the areal extent of future wetlands in some regions. The important variables that could affect wetland area and the emission period for northern and tropical wetlands are discussed below.

2.4.2.1 Northern Wetlands

The most important variables affecting wetland area and the emission period are temperature, precipitation, actual evapotranspiration (AET), and the depth to permafrost.[20]

[19] The majority of northern wetlands are non-riverine (not associated with a water body), and therefore the relative effects discussed here are ranked with this type of wetland ecosystem in mind. The relative effects of environmental variables on riverine northern wetlands may be slightly different than for non-riverine wetlands. Tropical wetlands, on the other hand, are predominantly riverine, and the relative effects shown here are ranked with this in mind.

[20] AET, or actual evapotranspiration, is defined as evaporation from soil plus transpiration from plants.

Exhibit 2-12

Effects of Environmental Variables on Wetland Area and Emission Period*

VARIABLE	NORTHERN		TROPICAL	
	AREA	PERIOD	AREA	PERIOD
Precipitation	4	3	4	5
Temperature	2	5	0	1
Actual Evapotranspiration	4	3	3	3
Human Impacts	3	2	5	3
Sea Level Change	1	1	2	1
Depth to Permafrost	4	1	0	0

* Rankings are relative and refer to within ecosystems (columns), not across ecosystems (rows). (0 = not important; 5 = very important)

Wetland Area. For northern wetlands, changes in precipitation will be critical in determining the areal extent of a wetland. However, AET and the presence of and depth to permafrost are also important (Hinzman and Kane 1992). For example, if permafrost near the land surface melts or recedes downward, the water can drain from the soil, destroying the wetlands. Similarly, increased AET could dry out wetlands. However, it is also possible that permafrost melting may enhance inundation in some areas (depending on topography), due to the collapse of the fragile wetland structure to the new level of the water table, once the water level has receded.

Emission Period. Since temperature provides the major seasonal signal in the far north, changes in temperature will likely be the most critical variable determining the length of the active season in northern wetlands (Exhibit 2-12). However, seasonal changes in precipitation and AET are also important, since the balance between summer and winter precipitation is important. If AET is higher than precipitation in the summer, then the emission period may become shorter. Alternatively, if precipitation only increases in the winter, there may be no change in the emission period, since most of the winter precipitation falls on a frozen wetland and is lost as spring runoff.

2.4.2.2 Tropical Wetlands

In tropical regions, precipitation largely controls the presence of seasonal wetlands and provides the major seasonal change. Even in more permanent systems, precipitation is critical to both the areal extent and emission periods of the wetlands (Exhibit 2-12). Tropical precipitation patterns are most often regional in scale and driven by large-scale atmospheric dynamics, such as the monsoons. Relatively small alterations in these atmospheric features (e.g., timing, location, frequency, intensity) could have significant impacts. Changes in temperature are unlikely to create large changes in areas or emission periods from wetlands because temperatures are high and fairly constant year-round.

Sea level rise could decrease methane emissions by reducing the area of wetlands in coastal locations. Because many tropical wetlands are located on relatively flat alluvial areas, rising sea level may have an impact on wetland area, type, and distribution, through simple flooding. Also, as sea level rises, and especially if precipitation decreases, the salinity of ground water may increase. A considerable data set on emissions from saline marshes across a relatively wide latitudinal range has been accumulated which clearly demonstrates that annual flux is strongly and negatively correlated with average soil salinity (DeLaune et al. 1983; Bartlett et al. 1987). In fact, methane release from most saline areas appears to be relatively minimal (Bartlett et al. 1985). Therefore, sea level rise is considered as a variable affecting area rather than emission rate because a wetland ceases to emit methane when it becomes salinated.

Human activities, such as agricultural and industrial development and water management programs, may have a large impact on wetlands in the future (Exhibit 2-12). Although most of these changes will affect the area of wetlands, there may also be significant changes in emission periods. For example, water control structures will alter patterns of seasonal inundation.

Most human development of wetlands is highly destructive of the original ecosystem area; however, water management and control practices may actually create additional source areas of CH_4. For example, tropical reservoirs in flood plains tend to be very shallow and subject to rapid siltation and they therefore have relatively short useful lifetimes. They become large shallow-lake systems with abundant organic material and potentially large CH_4 sources. In south Florida, for example, CH_4 emitted from the large water conservation areas created for agriculture effectively balanced the loss of CH_4 from natural wetlands due to drainage (Harriss et al. 1988). In addition, while most wetland agricultural development involves drainage, rice agriculture often involves replacing a natural wetland with a managed, anthropogenic wetland that produces even higher CH_4 emissions. Also, wetlands within riverine systems are linked by the river and human development to the entire system and are affected by activities elsewhere along the river, including the input of nutrients, organic materials, and pollutants, changes in sedimentation and water flow, and changes in plant species. All of these variables can significantly affect wetland characteristics and rates of CH_4 production and release.

2.5 Possible Future Scenarios for Methane Emissions

In order to develop possible future emission scenarios of methane from natural wetlands, it is necessary to outline some of the potential climatic changes over the next century. This section provides a brief discussion of changes in precipitation and temperature that are suggested by available climate models. It then develops some possible scenarios of changes in methane emissions as a result of these climatic changes.

2.5.1 Predicted Climate Change

The Intergovernmental Panel on Climate Change (IPCC) predicts that atmospheric concentrations of CO_2 will effectively double between 1990 and 2025-2050 (IPCC 1990). The potential effects of this doubling were examined through large-scale atmospheric General Circulation Models (GCMs). Models summarized by the IPCC yield estimates of global mean warming that range from 1.9° to 5.2°C with a doubling of CO_2 concentrations, and increases in global precipitation that range from 3% to 15% (Mitchell et al. 1990). Although these globally and annually averaged estimates suggest the likely size of changes, regional and seasonal estimates of climate change are more important for estimates of feedback mechanisms.

While many parts of the climate system are currently not well understood and various models show different increases in temperatures, particularly on a regional and seasonal scale, there are several large-scale features that appear in most model predictions. These features are summarized in the IPCC report (IPCC 1990):

- All models predict enhanced warming at higher latitudes in late fall and winter. In the more recent higher resolution models, warming over North America during the winter is predicted to be 4°C, increasing to 8°C over northeastern North America. Over Europe and northern Asia, warming is about 4°C, with some areas of much greater warming (e.g. eastern Siberia).

- According to most models, warming over northern mid-latitude continents in summer is greater than the global mean. Summer warming in more recent models is typically 4° to 5°C over the St. Lawrence-Great Lakes region of North America and 5° to 6°C over central Asia.

- Tropical warming is predicted to be less than the global mean and to have little seasonal variation. Typical estimates are 2°-3°C.

- All models indicate enhanced precipitation in the high latitudes and the tropics throughout the year, and in the mid-latitudes in the winter. For example, higher resolution models predict an increase of 10%-20% in precipitation averaged over land between 35-55° N.

- All models indicate a general increase in soil moisture in the northern high-latitude continents in the winter. Although models testing the effects of enhanced CO_2 suggest that both evaporation and precipitation will increase, rates of evaporation may be higher than precipitation, so that soils may actually experience greater drying.

- Most models predict an enhanced drying of surface soils in the northern mid-latitudes during the summer. In higher resolution models, soil moisture averaged over land between 35°-55° N decreased 17%-23%.

Exhibit 2-13 summarizes predicted temperature changes in arctic and boreal regions for several GCMs under a doubled CO_2 environment. In these Northern regions, the temperature may be expected to rise on the order of 4° to 8°C.

2.5.2 Developing Future Estimates of Emissions

The possibility of interactive feedbacks between natural sources of CH_4 and a changing climate has been recognized for some time (e.g., Hameed and Cess 1983). Clearly, the strong dependence of emissions on environmental variables, such as soil moisture, temperature, and organic supply, indicates that climate change will alter emission rates. Although a variety of

Exhibit 2-13 **Predicted Temperature Change (50-70° N latitude)** (units: °C)			
MODEL*	SUMMER (June, July, August)	WINTER (Dec., Jan., Feb.)	ANNUAL
GISS	2 - 4	5 - 12	4.2
GFDL	4 - 8	6 - 15	4.0
NCAR	0 - 4	6 - 10	4.0
UKMO	5 - 6	8 - 10	5.2

*GISS = Goddard Institute of Space Sciences, New York
GFDL = Geophysical Fluid Dynamics Laboratory, Princeton
NCAR = National Center for Atmospheric Research, Boulder
UKMO = United Kingdom Meteorological Office, Bracknell
Source: Mitchell 1989.

feedback "loops" have been suggested, namely between emissions from wetlands and elevated air temperatures (Hameed and Cess 1983), or between emissions and increased plant productivity due to higher CO_2 levels (Guthrie 1986), the magnitude of these effects continues to be highly uncertain.

While the best estimates of future emissions may in time result from process-based models that incorporate the major physical processes of hydrology and soil temperature dynamics, these efforts are not sufficiently advanced to provide quantitative estimates. Alternatively, a set of scenarios can be developed from expert judgement about the important processes governing emissions from the different wetland systems. These scenarios are discussed below, after a brief outline of current modeling efforts.

Process-Based Modeling

Modeling has been attempted for a few wetland systems and has yielded qualitative results. The primary physical components of these models are a hydrologic and a thermal model. While these types of models are common to the fields of agronomy, hydrology, and soil physics, they are not as developed for application to wetlands. Currently, only the direct climate effects of changing precipitation and temperature can be included in wetlands simulation models. Indirect effects of climate change on methane flux, such as plant community changes, have not been included. A limiting factor for these models is their requirement for substantial methane flux data over a range of climatic conditions so that the models can be calibrated based on actual measurements.

Model simulations have been performed for both northern and temperate wetlands. Roulet et al. (1992b) report that modeling of northern non-forested fens indicated that changes in moisture regime had significantly greater impacts than changes in temperature on emissions. In addition, the precipitation effects varied with fen type, since some fens had floating ground surfaces.

Harriss et al. (in press) examined the global response of CH_4 emissions in northern areas to temperature trends in historical data. The warmest and coldest years at single sites were calculated to produce large flux differences (warm years produced emissions more than 50% greater than emissions in cold years). However, when the model was expanded to include major northern wetland areas, asynchrony in variations in global temperatures resulted in much smaller annual flux variation. This model emphasizes the fact that an integrated, global perspective must be used to assess possible responses of wetlands to climate change. It also indicates that if temperatures increase in the future (deviating from the historical record), emissions could be expected to increase substantially.

Models have also been designed for temperate systems. For example, Pulliam and Meyer (in press) developed an empirical simulation model for swamps on the Ogeechee River floodplain in Georgia. The model was applied to historical climate and river hydrograph data and to simulated altered climates. Annual emissions were strongly linked to changes in flood plain inundation, and therefore, to river discharge. Future emissions were thus very sensitive to changes in precipitation, with results dependent upon the assumptions made about the response of evapotranspiration to elevated temperatures. These authors found that these hydrologic changes were more important than direct temperature effects on methane flux.

The EPA Office of Research and Development's Environmental Research Laboratory (ERL)/Athens intends to perform research over the next few years to provide estimates of future methane emissions from natural sources that are based on reproducible field data and methods.

Possible Future Scenarios

Several scenarios of future methane emissions have been developed based on limited empirical data and expert judgement of the important processes governing emissions from the different wetlands systems. These scenarios all focus on estimating potential increases in emissions from the northern wetlands. Scenarios have not been developed for tropical wetlands because a number of factors make predictions difficult in tropical regions. For example, these systems

- May be limited in carbon (little or no peat accumulation)
- Have not exhibited a relationship between increased temperatures and higher emission rates
- Are largely riverine, so that greater precipitation (remote and local) may affect inundation and wetland area in ways that are difficult to predict.

However, scientists have not ruled out the possibility that methane emissions from tropical wetlands could be significantly altered by climate change in the future. Changes in a number of variables, including precipitation, plant productivity, and human land use, could substantially increase or decrease methane emissions from tropical wetlands. To date, however, experts considered the situation in the tropics too complex and uncertain to make specific predictions.

Northern wetlands, on the other hand, can have large buildups of peat, and have large areas of marginally inundated wetlands that could be converted to much larger methane-producing areas. Furthermore, emissions in northern wetlands have been demonstrated to increase exponentially with temperature. Therefore, it is possible to make reasonable predictions from this region based on assumptions about temperature and water level.

The scenarios that have been developed are simplistic; they focus on changes in emissions from existing wetland areas and do not account for the expansion or contraction of wetland areas. They also do not account for the impact of a number of potentially important variables, such as sea level rise, and the impact of elevated carbon dioxide and ozone levels on plant productivity.[21] Scenarios for the northern wetland systems are presented below.

Lashof Scenario

Recently, Lashof (1989) looked at potential increases in methane emissions from northern wetlands as part of a larger effort to quantify climate feedbacks. A variety of simplifying assumptions were used to calculate the impacts of CH_4 emissions. For example, wetland area and type were assumed not to change over the 100-year time frame or longer. In addition, changes in the water balance were omitted, due to the uncertainty in the GCMs.

The changes in flux from northern wetlands were estimated as a function of the change in emission season length and the effect of increased temperatures. The function used to estimate the temperature effect was the same one suggested by Fung et al. (1991):

$$\text{flux}(t) = \text{flux}(t_o) * Q_{10}^{(T-To)/10}, \text{ where } T = \text{temperature and } t = \text{time.}$$

Based on several studies with a large range of estimates for the constant coefficient Q_{10} (1.4 to 20), a conservative Q_{10} range of 1 to 4 was chosen for this scenario, with 3 being the best estimate. This conservative range was selected because "it seems unlikely that the higher values reported in some of the literature would apply to annual average emission rates. Very high Q_{10} values probably reflect either the low-temperature start-up of methanogenesis (Q_{10} approaches infinity as the soil temperature approaches the freezing point) or seasonal variations involving covariance between temperature and other controlling variables (e.g. moisture and organic matter availability)."

Future temperatures for a world with doubled CO_2 were obtained from the GISS GCM (average summer temperatures in the high northern latitudes are estimated to increase 2° to 4°C). Based on this series of assumptions and a current northern wetland flux of 35 Tg/year, Lashof calculated that CH_4 emissions from wetlands would increase by 17 to 63 Tg/year, with a best estimate of 51 Tg/year, for a total increase of 150 percent.

[21] A doubling of atmospheric carbon dioxide could substantially increase plant productivity and methane emissions (Guthrie 1986). It has been suggested that, by itself, a doubling of CO_2 in wetlands could result in 30% more plant matter, 40% more soil organic matter, 50% more methane-producing microorganisms, and 50% to 100% larger methane emissions (Lamborg and Hardy 1983; Marvin Lamborg, pers. comm. 1992).

Oak Ridge Scenario

A workshop conducted by the Oak Ridge National Laboratory on April 4-6, 1988 estimated the upper bound of the increased net flux of CH_4 between northern ecosystems and the atmosphere under projected climate change conditions (Post 1990). The following assumptions were used:

- A doubling in the atmospheric concentration of CO_2 will cause temperatures to rise 5°C in the boreal and arctic regions. (This was believed to be a conservative estimate, particularly for the arctic region.)

- Although the participants acknowledged that expansion of wetlands may occur, for purposes of simplicity, they assumed wetland areas remained constant.

- Changes in methane emissions from currently dry tundra were not included in this estimate.

- Methane emissions due to the decomposition of organic matter released from melting permafrost were not included. The possibility that methane trapped in permafrost could be released by melting was also not accounted for.

- Although the assumptions used to generate emission estimates were thought to emphasize the most significant processes controlling carbon dynamics in northern environments, a variety of important processes, such as the direct effects of atmospheric CO_2 levels, species composition changes, and ecological, structural and organizational changes, could not be included in the calculations.

Two climate scenarios were examined: a 5°C warmer climate with unchanged water tables (warm/wet), and a 5° warmer climate with water tables lowered by 10 cm (warm/dry). Methane emissions from northern ecosystems responded in roughly the same manner to both scenarios. A calculation was not made for a warmer/wetter climate, or one with increased water tables, because it was assumed that such a climate would respond in the same manner as the warm/wet scenario.

Northern ecosystem responses were separated into two systems. Predictions were calculated in a different manner for each system:

> *Arctic Response.* Methane emission estimates in the arctic region were based on the assumption that permafrost melting and increased drainage, regardless of precipitation changes, would lower the water table, thus stimulating peat oxidation. Peat would be oxidized at a rate of about 1 cm of peat depth per year, over an area of $2x10^6$ km^2. (The carbon content of 1 mm of peat is assumed to be 65 g C/m^2.) While most of the increased soil respiration would be aerobic, or CO_2-producing, about 10% to 20% would be anaerobic, or CH_4-producing. Methane emissions from arctic ecosystems were predicted to increase by at least 130 Tg/yr, with the range probably closer to 170-340 Tg/yr (see Exhibit 2-14).

Boreal Response. For the boreal region, the average current microbial respiration rate is 267 mg $CH_4/m^2/day$. (It is not clear from the workshop report how much, if any, of this generated methane is oxidized, and how much is emitted.) Methane respiration in the boreal region is expected to increase by 10% with every 1°C rise in temperature. The increase in methane respiration will be entirely emitted to the atmosphere, while the amount of methane oxidized will remain constant. Boreal peat lands were predicted to emit an additional 32 Tg CH_4 per degree celsius of temperature rise. Thus, for a 5°C temperature rise, boreal emissions were predicted to increase 160 Tg/yr. Notice that this conclusion assumes a linear relationship between methane emissions and temperature rise, as opposed to the logarithmic or exponential response postulated in Section 2.4.1 of this report.

The estimates of potential increases in methane emissions are fairly large. These calculations are supported by the fact that the predicted rise in global methane release is similar to the observed methane rise that took place when comparable changes in climatic regimes occurred at the end of the last glacial period (Post 1990).

Exhibit 2-14

Oak Ridge Workshop Estimates of Increased Northern Ecosystem Methane Emissions
($Tg\ CH_4/yr$)

Ecosystem	Warm/Wet Scenario	Warm/Drier Scenario
Arctic (tundra)	130	130
Boreal (peatland)	160	160
Total	290	290

UNH Workshop Scenarios

Participants at the 1992 workshop at the University of New Hampshire (UNH) also attempted to assess the potential increase in the magnitude of methane emissions under possible future climate regimes.[22] Estimates are based on current CH_4 emissions of 35 Tg/year from the arctic and boreal zones (Bartlett et al. 1990; Fung et al. 1991; this report). Three different scenarios were developed to represent a range of possible future climates. They are all based on the assumption that atmospheric temperature will increase 4° to 6°C by the end of the next century. The scenarios differ only in their assumptions of changes in average soil moisture.

[22] In order to assess the potential impacts of climate change on natural wetlands, a workshop was held at the University of New Hampshire on March 10 and 11, 1992. A list of the wetlands researchers who participated in this workshop is provided in Appendix A.

Scenario 1 -- Warmer Temperature and Constant Water Table Scenario

The first scenario assumes that temperatures will increase by about 4° to 6°C by the end of the next century and that the level of inundation of the northern wetlands remains unchanged. It was agreed that a distinct, positive relationship exists between emissions and temperature along the lines of the Q_{10} model. However, there was general skepticism that the temperature effect alone would be as pronounced as it is in Exhibits 2-10 and 2-11 (i.e. $Q_{10} = 8$). The results of these experiments are believed to include the effects of other variables in addition to temperature. It was thought that a Q_{10} value of 4 was a more reasonable estimate, given the assumptions of this scenario. Therefore, with a temperature rise of about 5° C, methane emissions would be expected to double to approximately 70 Tg/yr.

Scenario 2 -- Warmer and Drier Scenario

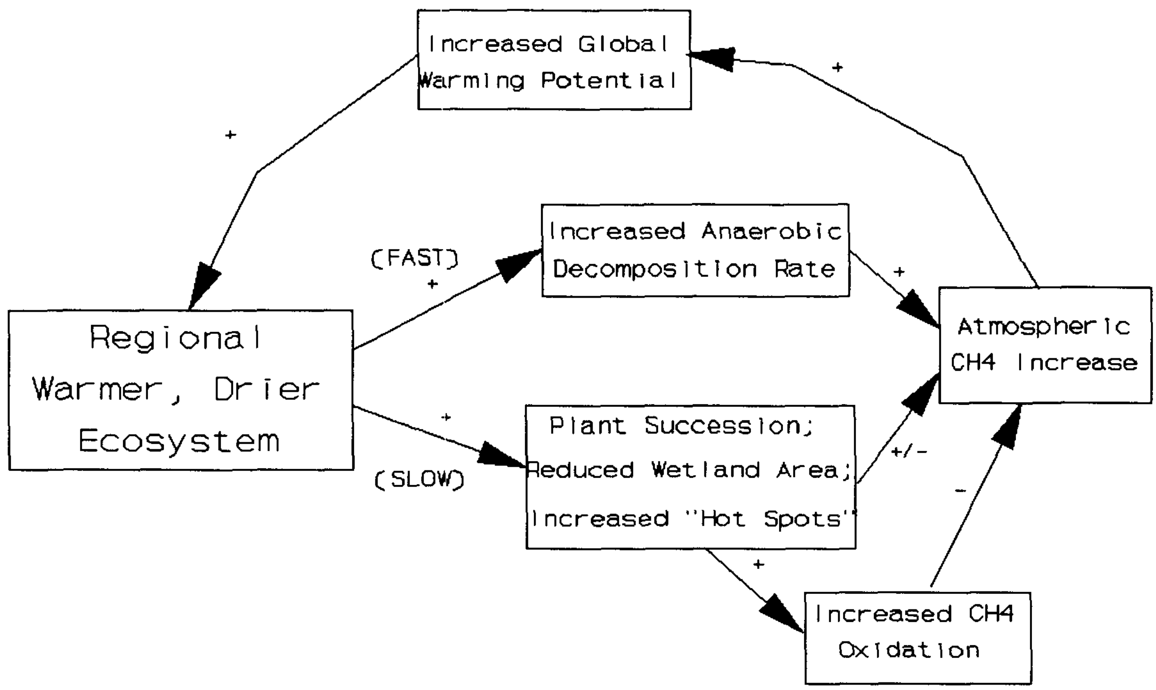
For a warmer and drier climate, assessing future emissions is more complex because a number of CH_4 feedback processes would be present. Exhibit 2-15 is a simplified schematic showing the major methane feedback processes in this climate scenario. (Note that gas hydrate and permafrost methane feedbacks are not shown here.) These processes include both fast and slow responses. For example, increased temperatures would quickly increase anaerobic decomposition rates and methane emissions. A slower response such as drying of wetlands leads to reduced wetland areas, thereby increasing aerobic respiration and decreasing methane emissions. Another slow response is the potential collapse of the peat structure once it has been sufficiently dried and subject to oxidation. This collapse could create a topographically more heterogeneous landscape with CH_4 "hot spots" -- low wet areas with very high CH_4 emission rates.

Under this scenario, it is also possible that the water table will drop significantly throughout the entire region as air temperatures increase by 4 to 6°C. In this case, emissions may be expected to drop to roughly 20 Tg/yr, in the short term (20-30 years), as surface soils dry and surface peats are decomposed and degraded. The increased oxidation rate of peat, however, could lead to a collapse of peat structure in some areas, and thus to an increase in topographical heterogeneity and a long-term increase in methane emissions. Emissions for the area could potentially double to 70 Tg/year. Admittedly, this prediction is not based on an equation but relies on scientific judgement. This method was chosen over the Q_{10} model because it was felt to more accurately represent the complex, and as yet unquantified, processes that would be involved in this scenario.

Similar results are obtained by looking more closely at the northern wetland ecosystems. For example, the boreal lowland areas of Hudson Bay and Siberia may be the regions that will experience the greatest changes under such a climate scenario. Assuming that these systems currently emit about 2 to 5 Tg/year, emissions could increase to between 10 and 30 Tg/year as a result of drying, followed by the collapse of the peat structure and the formation of methane "hot spots." The rest of the boreal region (representing 15 to 17 Tg/year) may produce lower emissions over the short term, followed by a return to their original emissions values. In total, emissions could reach about 40 to 60 Tg/year, which is an increase of 5 to 25 Tg/year.

Exhibit 2-15

Methane Feedback Processes in a Warmer, Drier Climate



Scenario 3 -- Warmer and Wetter Scenario

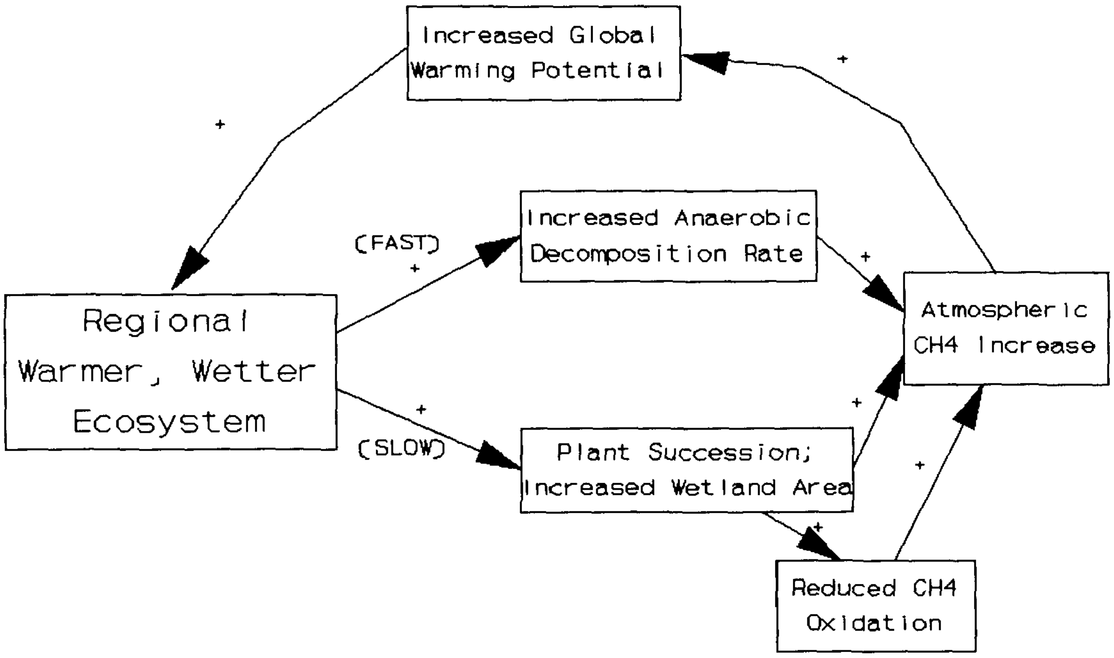
Fast and slow feedback mechanisms also exist in a warmer and wetter scenario (as illustrated in Exhibit 2-16). These mechanisms include increased emission rates (fast) and increased wetland areas (slow).

In this scenario, water tables are assumed to rise and air temperatures are assumed to rise by 4° to 6°C. Under these conditions, both the wetland area and the emission rate are likely to increase. Because of its wide distribution and large area, well-drained tundra may be a critical habitat in this scenario. Increased precipitation could convert these areas to significantly larger CH_4 sources, and emissions may rise to as high as 100 Tg/year.

The estimates in the three UNH scenarios are highly uncertain for a number of reasons. First, the change in the area of wet surfaces (inundated wetlands as well as lakes and ponds) is very tentative. This causes doubt in the emission estimates, because emissions from these sources are quite high relative to the surrounding terrain. Second, uncertainty arises from the implicit assumption that northern areas from which there are no flux data are similar to sites already examined. Third, these estimates are limited to direct climate effects and do not include possibly significant indirect effects, such as those due to changes in photoperiod

Exhibit 2-16

Methane Feedback Processes in a Warmer, Wetter Climate



length[23] or atmospheric CO_2 concentration.

Results from all of the northern wetland scenarios are summarized in Exhibit 2-17. While the range of predictions is large (5 to 290 Tg/yr), in all cases emissions are expected to increase over the next century.

2.6 Uncertainty and Further Research Needs

Much of the considerable uncertainty surrounding current and future methane emissions from natural wetlands can be reduced with additional research. The following section contains an estimate of the uncertainty in current emissions as well as a discussion of research needed to reduce this uncertainty. Section 2.6.2 addresses the difficulty in estimating future emissions and discusses several types of experiments that will make future predictions more accurate. Finally, Section 2.6.3 examines the phenomenon of methane uptake by soils and how this contributes to uncertainty.

[23] Photoperiod is the daily period when photosynthesis is the dominant process in a plant (approximately equal to daylight hours). Plants at very high latitudes may respond differently to climate change than those at lower latitudes due to the difference in photoperiod during the summer months.

Exhibit 2-17 Summary of Northern Wetland Emission Scenarios*			
Author	Warmer/Drier	Warmer/Wet	Warmer/Wetter
Lashof		17 - 63	
Oak Ridge Workshop	290	290	
UNH Workshop	5 - 35	35	65

* Values shown are for the change in emissions in Tg CH_4/yr.
Sources: Lashof 1989; Post 1990; this report.

2.6.1 Current Emissions

The amount of methane currently being emitted from natural wetlands is uncertain but the range of estimates is believed to be fairly accurate. This is due to the similarity between the estimates for global emissions derived in this report and in several previous efforts. While most of these efforts are based on similar data and assumptions, others used very different methodologies (e.g., Fung et al. (1991) arrived at a similar estimate using a tracer model).

Quantifying Uncertainty

It is difficult to perform a rigorous statistical analysis of the uncertainty in the current emission estimates derived in this report. An approximate attempt to estimate the upper and lower bounds of the current emissions from each of the wetland types follows. These bounds are based on ranges of uncertainty estimated for (1) the emission rate and (2) wetland area. Uncertainty in the emission period is not included in these ranges. The purpose of this exercise is not to give a definitive range for current emissions but rather to convey the approximate magnitude of such a range.

Emission Rate Range. A common statistic used for estimating the variability in a population is the standard error of the mean (see Exhibit 2-18). The upper and lower bound of the emission rate is one standard error of the mean in each direction of the average. The standard errors are considerably higher for tropical wetlands (about 44% of the mean) than for northern wetlands (about 25% of the mean). Exhibit 2-18 suggests that a major source of uncertainty in current emissions is the emission rate rather than the area of emissions. Matthews and Fung (1987) and Aselmann and Crutzen (1989) also identify the emission rate as the major source of uncertainty (Matthews, pers. comm. 1992).

Wetland Area Range. The range of areal uncertainty is derived not by statistical analysis but by comparing small increments of areal estimates provided by two separate researchers who used different methods: Matthews and Fung (1987), and Aselmann and Crutzen (1989). The areal estimates of Matthews and Fung (1987), which are used as the baseline in this report, were derived by combining three independent digital data bases for (1) soils, (2) vegetation, and (3) inundation.

Aselmann and Crutzen (1989) used regional wetlands surveys and monographs to derive wetland areal estimates. While these two research teams used different vegetation classifications, they both give total wetland areal estimates by 10° latitude bands. Thus, by taking the smaller of the two estimates for the five latitude bands in the tropical region, a lower bound for tropical area is estimated. Similarly, lower and upper bounds are estimated for temperate, boreal, and arctic regions. According to this method, the tropical wetland area ranges from 14 to $25 \times 10^{11} m^2$, and the northern wetland area ranges from 88 to $105 \times 10^{11} m^2$. This method for estimating the areal range was chosen because neither Matthews and Fung (1987), nor Aselmann and Crutzen (1989) give a range for the area of wetlands. It is entirely possible that the areal range derived here does not incorporate the full degree of uncertainty surrounding wetland areas.

Emission Period Range. The emission periods used in this analysis are from Matthews and Fung (1987), who did not estimate a range for period used. While it is generally agreed that the Matthews and Fung values are approximations, a reasonable method for estimating uncertainty in period was not found.

Given the uncertainty ranges for emission rate and wetland area, the range of uncertainty in total wetland methane emissions is estimated to be from approximately 70 to 170 Tg/yr (see Exhibit 2-18). This is a rough estimate since not all sources of uncertainty could be quantified. More of the uncertainty comes from the tropical region (where emissions range from 34 to 118 Tg/yr), than from northern wetlands (29 to 52 Tg/yr).

Research Needs

Uncertainty in current emissions can be reduced with more and longer term studies. Because regional flux comparisons show that data from one area cannot be easily extrapolated to other regions, a primary research need is data from large wetland areas from which there are currently little or no data. Also crucial to the understanding of methane fluxes are multi-year flux and environmental variable studies such as the report by Whalen and Reeburgh (in press). These types of studies need to be conducted on decadal time scales, which offer the only reasonable way to assess natural variability in flux and the integrated response of the wetland ecosystem. Long-term flux studies also permit the examination of the complex relationships among variables controlling the flux. More specific data deficiencies and research needs are discussed below for tropical, temperate, and northern wetlands.

Tropical Emission Data

Uncertainty in current emissions from the tropics is greater than the uncertainty surrounding the temperate or northern regions. Less sampling work has been done in the tropics.

Important tropical regions from which there are no data include: (1) large African wetlands, such as the Sudd, the headwaters of the Nile River, and the Okavango, (2) the Pantanal region in Brazil and Bolivia, and (3) Indonesian peat swamps. On the other hand, a considerable and relatively consistent data set has now been assembled for the Amazon (n = 788 and nearly annual coverage).

Exhibit 2-18

Uncertainty in Current Wetland Emission Estimates

Ecosystem	Average Emission Rate (mg CH_4/m²/d)	Std Error of Mean	Low Emission Rate[a]	High Emission Rate[b]	Area ($x10^{11}m^2$)	Low Area[c]	High Area[c]	Average Emissions (Tg CH_4/yr)	Low Emissions (Tg CH_4/yr)	High Emissions (Tg CH_4/yr)
Tropical Wetlands					19	14	25	65	34	118
Flooded Forests	165	70	95	235	10	8.0[d]	14[d]	31	14	60
Non-For. Swamps	233	52	181	285	8	6[d]	11[d]	33	20	55
Open Water	148	102	46	250	0.5	0.4[d]	0.7[d]	1.3	0.3	3.1
Temperate[e] Wetlands					4.1	3	6	5	5	5
Northern Wetlands					88	88	105	38	29	52
Boreal	87	18	66	108	15	15	17	20	14	28
Arctic	96	21	78	114	15	15	16	14	11	18
Drained Tundra	7	2	5	9	59	59	72[f]	4	3	6
Total					111	83	167	109	68	175

[a] Low Emission Rate = Average Emission Rate - Standard Error of the Mean
[b] High Emission Rate = Average Emission Rate + Standard Error of the Mean
[c] Low and High Areas derived from comparison of Matthews and Fung (1978) and Aselmann and Crutzen (1989) wetland data bases
[d] The upper and lower bounds of the three tropical wetland types are assumed to have the same percentage deviation from the baseline as the larger tropical region.
[e] Due to the relatively minor contribution to global emissions from temperate wetlands, upper and lower bound are not calculated here for temperate systems.
[f] High Area for drained tundra taken from Whalen and Reeburgh (1988).

Yet, while average emission rates have been well characterized for Amazonian wetland types, the area and emission period of these types are uncertain. The emission period is determined primarily by flood waters, which annually inundate and recede from the flood - plain. Seasonal remote sensing data of vegetation and inundation throughout the flood plain will greatly reduce these uncertainties.

Temperate Data

While temperate wetlands make only a small contribution to global emissions, they are well-characterized in terms of emission rates, particularly in the U.S. Furthermore, extensive ancillary data bases in the U.S., containing data such as air temperature, rainfall, and river discharge rates have facilitated attempts to link patterns in wetland emissions with environmental variables in general. However, despite the large data set available, significant uncertainty is associated with emissions from this region. The uncertainty stems from the fact that while most studies in the temperate zone have had year-round sampling programs, few of these studies have sampled over a period of several years. Thus, the true, long-term average emission rate may not be as well defined as it might seem.

Another source of persistent uncertainty is the error caused by using measurements from a relatively small area to represent a much larger one. Uniformity in emissions patterns from a small area can give the false impression that emission patterns from the larger area are also fairly uniform. For example, working in the Florida Everglades, Bartlett et al. (1989) found that measurements collected within a few meters displayed significantly less variance than those more widely separated (100 m or more). These results suggest that (1) the range of average methane emission rates derived from the study would lead to conservative estimates of the confidence in the means and (2) that spatial, within-system variability could introduce significant uncertainty in extrapolations to larger scales. This level of variability illustrates some of the problems inherent in simple, latitudinally-averaged emission estimates.

Small-scale variability has also been observed for emission periods. Wilson et al. (1989) noted that wetland types within a relatively small area in Virginia had different emission periods. The timing of the emission period also varied among sites.

If these well-researched temperate and subtropical sites can serve as models for those that are more remote, variability in the emission rate and period (on scales ranging from one m^2 to regional) greatly increases the uncertainty in large-scale estimates and should be addressed in all sampling programs.

Northern Data

Estimates of emissions from northern wetlands are uncertain because of year-to-year variability and winter emissions, as well as large-scale extrapolation between heterogeneous wetland systems (e.g., comparison of Minnesota and Hudson Bay Lowlands data). Uncertainty in this region is greater than in the temperate region, but not as large as in the tropics.

Year-to-Year Variability. The majority of data from the north was collected during a single season. Therefore, little is known about annual variability. Multi-year studies have been conducted at only two sites: Marcell Forest (in the boreal zone) and Fairbanks (in the arctic zone). Data from these sites suggest that emissions may vary by as much as an order of magnitude from year to year.

Winter Emissions. While little work has been done on this subject, emissions during the winter months (November through March) can contribute as much as 20% of the annual flux from northern wetlands, even under heavy snow cover (Dise, submitted (b)). The contribution of winter emissions to annual fluxes appears to be highly variable by year and by site. Heavy early snow and the depth of the snow-pack which insulates surface soils may be important controls on flux (Dise, submitted (b)). Since more significant winter fluxes were observed in Minnesota (boreal) than in Fairbanks, Alaska (arctic), they may occur more frequently as winter temperatures become more moderate in the boreal region. If winter season emissions from the boreal zone are disproportionately larger than those from the arctic, differences between the two regions may be greater than they now appear.

Much of this uncertainty, however, can be reduced with additional data from both a broader variety of sampling sites and from year-round, multi-year data sets. Additional survey measurements of flux are needed in areas such as the vast Siberian lowlands because regional comparisons have shown that extrapolations from one region to another are unreliable. Furthermore, recent data has indicated that moist-to-dry boreal wetlands and boreal and arctic lakes can contribute significantly to global emissions. However, it is not possible to calculate the contribution from these systems at this time because the areas of these habitats are not known. A survey of the areal extent of these ecosystems is necessary. The volume of data accumulated in only the last few years suggests that progress in decreasing uncertainties can be rapid.

2.6.2 Future Emissions

Estimates of potential future emissions from wetlands are much more uncertain than current estimates. This greater degree of uncertainty is indicated by the large range of predictions that have been made for future northern wetlands. However, additional research in several areas could help reduce the uncertainty in current emission estimates and in future projections.

Environmental Variables

Only the direct climate effects of changing precipitation and temperature have been included in the simulation models and expert predictions. However, several other environmental variables could play an important role in future emissions. Poorly understood effects that could significantly affect future emission scenarios include:

Solar Inputs. Alterations in solar inputs such as variations in cloudiness (with or without changes in precipitation) could affect AET and plant productivity, and therefore alter emissions. Because evapotranspiration may be a critical variable controlling inundation in many wetlands, an understanding of the response of AET to changed climates is important (Dooge 1992).

Natural Fires. The severity and frequency of natural fires in northern latitudes could increase as a result of climate change, especially if wetlands become drier. Increased natural fires could have a large, positive effect on wetland methane emissions (Post 1990).

Precipitation Dynamics. The relative balance between precipitation falling in the winter, as snow, and in the summer, as rain, is important. Since snow is accumulated on the frozen ground surface and then released as a pulse during spring warming, its effect on soil moisture is significantly different than that of rainfall, which is more likely to be absorbed into the soil. Knowledge of regional topography and relative elevation is also critical to predicting inundation. Currently, these types of data are quite difficult to obtain for most wetland areas.

Plant Community. Methane emissions appear to be strongly linked to the type and amount of wetland plants present in a variety of environments (Sebacher et al. 1985; Whiting and Chanton 1992). It is possible that significant changes may occur in these plant communities, either through changes in species or through greater productivity due to increased temperature, moisture, or atmospheric CO_2 levels (Guthrie 1986; Idso 1989). This possibility suggests that these linkages need to be better understood for more species and in more habitats.

Empirical Data Needs

While the wide array of environmental variables and their uncertain relationships to methane emissions make predicting future emissions difficult, there are a number of observational and manipulation experiments that can help resolve uncertainty.

Multi-Year Observations. Multi-year flux and environmental variable studies such as the report by Whalen and Reeburgh (1992) are crucial to the understanding of CH_4 flux. These types of studies need to be conducted on decadal time scales to assess natural variability in flux and the integrated response of the wetland ecosystem. Long-term flux studies also permit the examination of the complex relationships among variables controlling flux.

Indicator Ecosystem Observation. It may be useful to focus some long-term research on an "early warning" or indicator ecosystem, which could detect possible climate change / flux relationships. A useful ecosystem for this purpose would have a fairly long flux data base to assess "natural" variability, and would have to cover fairly large spatial scales (to ensure that changes are widespread). The extensive areas of moist-to-dry tundra in the northern latitudes may be a reasonable choice for these purposes since they are "poised" between being a CH_4 source or a sink and lie within a region projected to undergo significant climate change.

Human Impacts Observation. The long-term effects of human wetland modification on CH_4 flux are largely unknown. It is therefore important to examine emissions from a variety of impacted areas over long time scales and histories of plant succession. Modified areas should include such systems as burned wetlands, reservoirs, areas under new water management controls, and riverine wetlands subjected to changed patterns of nutrient inputs and/or sedimentation. The variables that need to be considered in evaluating human impacts include the rate of change of environmental modifications, possible interactions among climate change and human impacts, watershed changes, higher CO_2 levels, increased pollution/nutrients, plant species changes, and altered temperatures.

"Natural" Ecosystem Manipulation. Natural ecosystem or mesocosm manipulation of environmental variables offers another way to examine flux relationships (Billings et al. 1983). Such experiments typically involve artificially altering one variable (e.g., ambient carbon

dioxide) in an otherwise unchanged natural ecosystem. "Natural" experiments are likely to be the most realistic and the most easily applied to the real world.

Laboratory Manipulation. Small systems or cores and laboratory manipulations may be helpful in interpreting results from larger systems, but in themselves are so artificial and isolated that they are difficult to extrapolate realistically. More extensive evaluation of correlations between CH_4 flux and environmental variables in models to predict responses under changed climates, or for extrapolations into unknown areas, is needed.

2.6.3 Methane Uptake in Wetlands

Adding to the uncertainty about the net role wetlands will play in future atmospheric methane concentrations is the fact that wetlands can act as methane sinks as well as sources. In addition, the amount of atmospheric methane absorbed by wetlands could be altered as the climate changes.

In addition to oxidizing locally generated methane before it escapes into the atmosphere, wetlands can oxidize or absorb atmospheric methane. Aerobic (oxygen-present) surface soil conditions are conducive to methane oxidation. Therefore, uptake of atmospheric methane can take place when a seasonal wetland, such as a seasonally flooded forest, is dry at the air-soil interface. In this situation, such a wetland may be a net sink of methane. Other non-methane-producing ecosystems are permanent sinks of methane. The global soil sink is currently estimated at 10 to 50 Tg CH_4/yr (IPCC 1990). Similar to global methane emissions, the global uptake of methane is determined by the uptake rate, the uptake area, and the uptake period.

Uptake Rate. Since methane uptake in natural soils was first observed in 1982 (Harriss et al. 1982), this phenomenon has been extensively studied. One of the most striking features of the data is the overall similarity of uptake rates across ecosystems and latitudes (see Appendix G). Average or median uptake rates are almost always less than -5 mg $CH_4/m^2/d$, and usually less than -2 mg $CH_4/m^2/d$. Thus, while methane emission rates can vary over several orders of magnitude (0 to 2000+ mg $CH_4/m^2/d$), methane uptake rates can vary only slightly (0 to -5 mg $CH_4/m^2/d$).

Although CH_4 oxidation in soils is a microbial process, methane uptake rates appear to be controlled not by biological or environmental variables, but by rates of diffusion in soils (Steudler et al. 1989; Born et al. 1990; Crill 1991; Goreau and de Mello 1985; Born et al. 1990; Keller et al. 1991). Of course, soil diffusion is greatly affected by inundation. Therefore, methane oxidation rates could be affected by climate change but not to the extent that emission rates can be altered.

Uptake Area and Period. The period and areal extent of methane uptake from non-methane-producing ecosystems, such as upland forests and dry savanna, are not likely to shift with climate change. However, the period and area of uptake from wetlands could change if the period and area of methane emissions from wetlands are altered. For example, if wetlands become drier and the period of emissions decreases, then the period of uptake could increase.

Future changes in methane uptake could act as a magnifier of changes in methane emissions: if, for example, a wetland location dries out and ceases to emit methane, it may become a negative emitter (uptake). Conversely, a location that is currently a weak sink (uptake) could become a strong source (emission) if it is sufficiently inundated. Thus, future predictions of methane emissions from wetlands are made slightly more uncertain by the magnifying effect that methane uptake could have on changes in the wetland area and the emission period. However, changes in global soil uptake of methane are likely to be small in comparison with changes in global methane emissions.

CHAPTER 3

NATURAL FOSSIL SOURCES

There are two natural fossil sources of significance: gas hydrates and permafrost. These sources are estimated to emit about 3 to 5 Tg of methane annually, representing about 3% of emissions from natural sources and 1% of total methane emissions. Currently, fossil sources do not contribute significantly to atmospheric methane concentrations. However, emissions from fossil sources could increase by more than two orders of magnitude as a result of climate change, making them the largest single source of methane.

This chapter presents background information about hydrate and permafrost sources of methane, provides estimates of current emissions from these sources, and discusses the potential increases in emissions as a result of climate change.

3.1 Gas Hydrates

The current and future potential for the methane release from gas hydrates depends on several important factors. These factors include the total quantity of methane reserves stored in hydrates in different regions, the stability conditions required to maintain these reserves in storage, and the extent to which the environmental conditions of existing hydrates could be altered in the future.

3.1.1 Background

In order to understand the factors affecting gas hydrates, it is useful to first understand the nature and origin of gas hydrates.

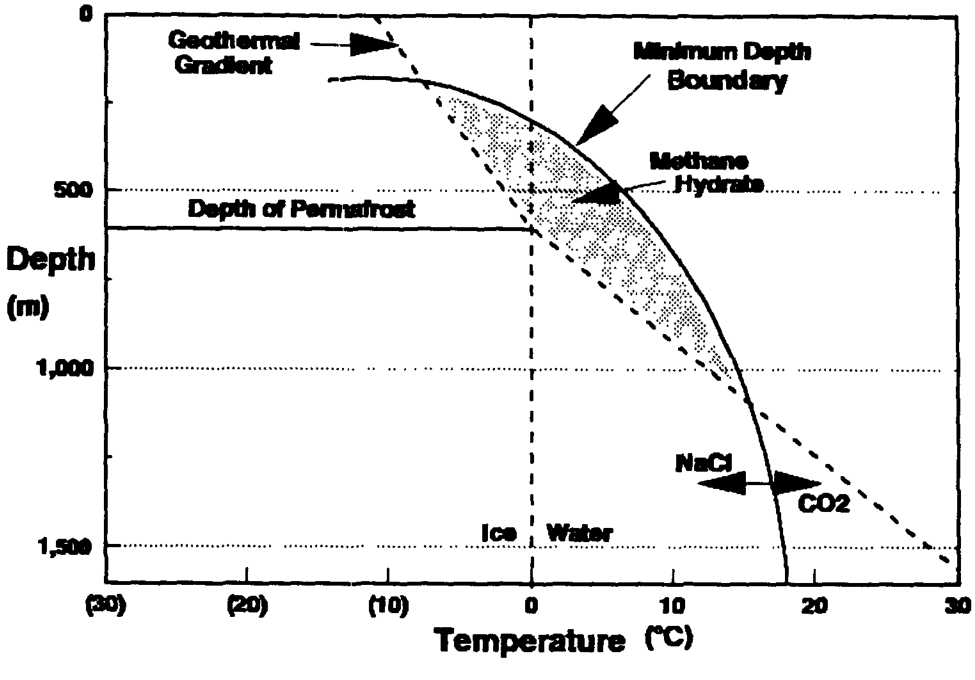
What are Gas Hydrates?

Methane gas hydrates are solid structures composed of rigid cages of water molecules that enclose methane molecules. Ordinarily, when water freezes, it forms ice in a hexagonal crystal structure. However, when a threshold concentration of methane or other gases is present, and pressure is sufficiently high, water crystallizes in a cubic lattice that traps the gas molecules. The hydrate structure is sensitive to temperature, salt, and other impurities, and is only stable under pressure equivalent to at least 180 m of soil overburden (Bell 1982). The ratio of CH_4 to H_2O in a methane hydrate can be as high as 1 to 5.75. Because of the high CH_4:H_2O ratio, a unit volume of hydrate can contain up to about 170 times as much mass of methane as a unit volume of pure methane gas at standard conditions (Kvenvolden 1991e).

Methane gas hydrates are formed when methane is created within or enters into the zone of hydrate stability (see Exhibit 3-1). The source of methane for the formation of gas hydrates may be either microbial or thermal in origin. Microbial methane is created by the anaerobic digestion of organic matter by microorganisms in shallow, oceanic and continental sediments. Thermogenic methane is produced by the thermal alteration of organic matter that is deeply buried in sediment.

Exhibit 3-1

Hydrate Stability Zone: Continental Case



Source: Kvenvolden and Mc Menamin (1990)

Methane Hydrate of Microbial Origin

As described in the chapter on natural wetlands, methane of microbial, or biologic, origin is created by the decomposition of organic matter in wet, oxygen-depleted sediment. In the oceanic case, the organic matter is called "marine humus", and consists primarily of the decomposed tissue of tiny organisms such as plankton and nekton. This humus falls to the ocean floor, where it is buried by sediment at the rate of 10-20 cm/100 yrs (Revelle 1983). Once it is buried, anaerobic conditions soon prevail and the organic matter is digested by methanogenic bacteria. If more methane is produced than can be dissolved by the water in the pores of the sediment (80-160 mmol CH_4/L), and temperature and pressure conditions are met, then the methane is converted into methane hydrate.

Methane Hydrate of Thermal Origin

Thermogenesis of methane takes place under high pressure (>200 bars) and temperature (>80-120°C) (MacDonald 1990). Typically, such conditions exist well below the zone of hydrate stability. When methane is created in this manner, it enters hydrate form only when a migration pathway exists from the lower sediment to the upper sediment layer (Kvenvolden 1988). Tests of the isotopic composition of the methane extracted from hydrates at several depths and locations worldwide reveal that most of the methane is microbially generated, not thermally produced (MacDonald 1990).

Gas Hydrate Reserves

The quantity of methane stored as gas hydrates is substantial. These methane reserves are estimated for three major types of hydrates (see Exhibits 3-2 and 3-3):

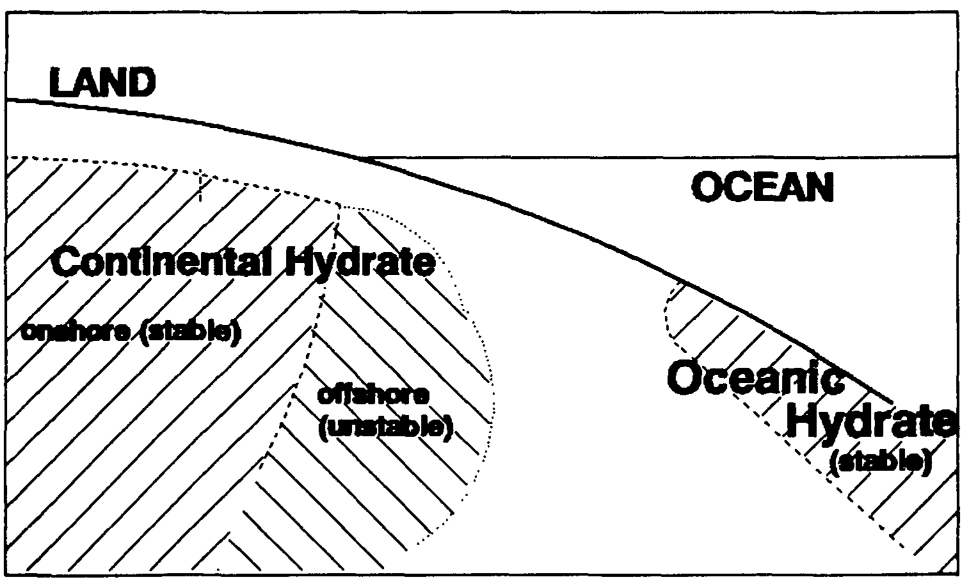
Oceanic Hydrates. Oceanic hydrates are found in underwater sediments of the outer continental margin at all latitudes. They only occur where the ocean floor is greater than 300 meters below the ocean surface. They are located between the ocean floor and a sub-bottom depth of about 1,100 meters, depending on the ocean-bottom temperature and the geothermal gradient (Kvenvolden 1991e).

Onshore Continental Hydrates. Continental, or permafrost-associated hydrates, can occur within or below the permafrost zone, and are found onshore at high latitudes, at depths of about 200 - 1,200 m below the surface of the earth in regions of continuous permafrost (Kvenvolden 1991b).

Offshore Continental Hydrates. Continental hydrates can also be found offshore, on the nearshore continental shelf, where melting subsea permafrost has persisted since times of lower sea level. Since the last ice age, 18,000 years ago, sea level has risen about 100 - 125 m, and the temperature of the present shelf has risen about 15°C (Hill et al. 1985; Kvenvolden 1991a; Osterkamp, personal communication).

Exhibit 3-2

Relative Location of Hydrate Types



The existence of gas hydrates has been verified using a number of methods such as direct observation and seismic reflection methods. Gas hydrates are known or inferred to exist throughout polar onshore and nearshore permafrost regions, and in the oceanic outer continental margin sediments of all seven continents.

Estimates of methane hydrate reserves vary widely. Oceanic methane estimates range from 2.3×10^6 Tg (McIver 1981) to 5.5×10^9 Tg (Dobrynin et al. 1981), and continental estimates range from 1×10^5 Tg (Meyer 1981) to 2.4×10^7 Tg (Dobrynin et al. 1981). However, a number of recent, independent estimates, based on an expanded data set, have converged on estimated methane reserves of about 1×10^7 Tg for oceanic reserves and 5×10^5 Tg for continental reserves (Kvenvolden 1991e; MacDonald 1990). This amount of methane is more than two thousand times the current atmospheric reservoir of methane, and about twenty thousand times the current annual emissions. Of the continental hydrates, about 70% are onshore and 30% are offshore (Kvenvolden 1991e).

Exhibit 3-3

Methane Hydrate Reserves (Tg CH_4)

Hydrate Type	Range of Estimates	Best Estimate
Oceanic	2.3×10^6 - 5.5×10^9	1.0×10^7
Cont. (Onshore)	1×10^5 - 2.4×10^7	3.5×10^5
Cont. (Offshore)		1.5×10^5

Stability of Gas Hydrates

Gas hydrates are stored or maintained in a "stability zone." The stability zone is the layer in the sediment where the temperature and pressure conditions are sufficient to support hydrates. The minimum depth of hydrate stability is proportional to pressure and inversely proportional to temperature (i.e., hydrates are stable if the pressure is sufficiently high and the temperature is sufficiently low). Hydrates do not exist at the surface because, even under the coldest conditions, the pressure is not sufficient. Conversely, hydrates do not exist at great depths because temperature increases with depth in sediment (according to a geothermal gradient of 0.016 to 0.053°C/meter), and by about 2 kilometers below the sediment surface, temperature is almost always too high for the hydrate structure to be viable.

The thickness of this stability zone may be anywhere from 0 to 2 kilometers, and can expand or contract in response to changing temperature and pressure conditions. If the zone expands (as a result of increased pressure and/or decreased temperature), it can incorporate more methane from the surrounding sediment. Conversely, if the zone contracts (as a result of decreased pressure and or increased temperature), large amounts of methane can be liberated from hydrates into the sediment and can migrate into the atmosphere.

3.1.2 Current Emissions

Oceanic and onshore continental reserves are believed to be stable at present, which means that they are not currently emitting methane. However, offshore continental shelf reserves are currently unstable, and may emit 3 to 5 Tg of methane annually to the atmosphere (Kvenvolden 1991e; IPCC 1992). These emissions result from climate changes that occurred within the last 18,000 years, the time since the last glaciation. Since that time, sea level has risen about 100 to 125 meters, inundating large areas of permafrost which contain methane hydrates. Inundation has increased the pressure in this region by about 9 atmospheres, which would be expected to increase the stability of the hydrates. However, over the same period, the temperature at the sediment surface has increased by 15°C, which is more than enough to offset the increase in pressure and destabilize the hydrates (Kvenvolden 1991e). Due to the slow rates of downward thermal diffusion in sediments, this temperature change is still in the process of penetrating downward, degrading the permafrost and associated gas hydrates. The emission estimate of 3 to 5 Tg CH_4/yr was determined by assuming that the difference between the calculated and the known amount of methane in sub-sea permafrost hydrates (160,000 - 43,000 = 117,000 Tg) has been uniformly released over the last 18,000 years (Kvenvolden 1991e).

These estimates assume that the methane being liberated from the gas hydrate form is released into the atmosphere. It is possible, however, that some or all of this gas is not actually emitted to the atmosphere. Instead it is oxidized or absorbed within the sediment.[24] If the methane is not trapped in sediment or oxidized in the water column, it could escape to the atmosphere and contribute to the atmospheric burden of methane (Cicerone and Oremland 1988; Kvenvolden 1991e).

Estimates of methane release from offshore, continental shelf gas hydrates may be substantiated by measurements of the methane concentration of 17 bottom-sediment samples from the Alaskan Beaufort shelf (Harrison Bay). Concentrations ranging from 4,000 - 20,000 nl CH_4/l water were observed (Kvenvolden et al. 1991a). The equilibrium concentration of CH_4 relative to the atmosphere is only 70 nl/l. Other researchers have measured bottom-water methane concentrations as high as 1,100 nl/l H_2O on the Canadian Beaufort shelf, in an area of known hydrate occurrence. The unusually high methane concentrations observed in the Beaufort shelf suggest a source of methane within sediment of the nearshore continental shelf. The source could be gas hydrates (Kvenvolden et al. 1991a).

Further evidence that hydrates may currently be releasing methane to the atmosphere may be provided by Clarke et al. (1986), who suggest that some 150 methane plumes observed by NOAA satellites near Bennett Island in the Soviet far Arctic are produced by hydrates. There are other plausible explanations for these plumes. It has been suggested, for example, that the plumes may be water vapor--not methane (Kvenvolden, pers. comm. 1992). Further research is necessary to confirm Clarke's hypothesis.

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[24] Oxidation is the chemical conversion of methane and oxygen to carbon dioxide and water. Absorption means that the methane is dissolved in water or trapped in soil and can be oxidized or emitted at a latter date.

3.1.3 Future Emissions

Due to their proximity to the earth's surface (<2000 m), gas hydrates will eventually be affected by global warming, and methane emissions from this source are likely to increase if temperature significantly rises. While pressure on hydrates is also expected to change as a result of sea level rise and the melting of polar ice caps, temperature changes are likely to be far more significant than changes in pressure in determining future emissions during global warming.

The Intergovernmental Panel on Climate Change has predicted that an effective doubling of atmospheric CO_2 between 1990 and 2025 to 2050 will cause the global mean temperature to increase 1.9°C to 5.2°C (Mitchell et al. 1990). The temperature increase in the polar regions, where all onshore and offshore continental shelf hydrates are believed to occur, is expected to be double the global mean, or about 3°C to 10°C (IPCC 1990).

Using a variety of assumptions about the magnitude of temperature rise, gas hydrate reserves, and the thermal properties of oceans and sediment, several researchers have developed scenarios for future emissions of methane from this source due to climate change. The scenarios have been divided into continental and oceanic scenarios, and their key features are summarized in Exhibits 3-4 and 3-5. The scenarios predict the expected annual rate of methane emissions once global warming has reached the hydrate zone. Most of the scenarios also provide a rough estimate of the time lag expected before warming would reach the hydrate zone.

Continental Hydrate Scenarios

The scenarios for the continental hydrates, developed by four different researchers, are presented below.

Kvenvolden's Scenario: 150 Tg CH_4/yr

Kvenvolden (1991e) reports that the most likely additional future source of methane emissions from hydrates is the region of subsea permafrost, which may be currently degassing. The accelerated temperature rise that would result from the expected climate change could penetrate to the level of subsea permafrost and increase the current rate of emissions from these hydrates by an order of magnitude (from 4-5 Tg CH_4/yr to 40-50 Tg CH_4/yr). This increase in the emission rate would be expected to take place sometime after the twenty first century.

Similarly, this scenario predicts that onshore gas hydrates will eventually be destabilized by climate change. The rate of emissions from this source is predicted to be twice that of subsea permafrost hydrates, or about 100 Tg CH_4/yr. The time lag before this emission rate is achieved is greater than the lag for subsea permafrost emissions and ranges from hundreds to thousands of years (see Exhibit 3-5).

MacDonald's Scenario: 50 Tg CH_4/yr

Based on the analysis of recent temperature changes in the Arctic by Lachenbruch and Marshall (1986), MacDonald (1990) assumes that Arctic surface temperature has risen 2°C since 1880 and that temperature will increase another 2°C by 2080. By the year 2090, this temperature disturbance will have reached the more shallow sections of the hydrate stability zone and methane release will begin. McDonald's forecast predicts that the entire continental hydrate zone will be destabilized at an average rate of 30 cm/yr or about 0.01% of the total reserve per year. The total continental reserves are estimated at 5.3×10^5 Tg CH_4, thus the annual emissions could be 50 Tg CH_4/yr (see Exhibit 3-5).

Bell's Scenario: 300 Tg CH_4 /yr

Bell (1982) has developed a scenario in which a doubling of atmospheric CO_2 causes the air temperature in the high latitudes to increase by 10°C. Consequently, the permafrost between the -5°C and -15°C isotherms of annual mean air temperature becomes unstable. As the permafrost is destabilized, temperature rise is transmitted to the hydrates, which exist within and below the permafrost zone. Destabilization and degassing from the hydrates begins within a few hundred years of the initial air temperature rise. The affected area comprises about half of the total area of northern permafrost, and it also contains about half of the total continental hydrate reserves (Total continental reserves = 2.7×10^6 Tg CH_4). Bell estimates that all of the methane in this region will be released uniformly over 4000 years (see Exhibit 3-5).

Nisbet's Scenario: > 100 Tg CH_4 /yr

This scenario is based on the assumptions that CO_2 concentration will quadruple within a century and the mean annual air temperature in the Arctic Islands will increase by 19°C, from -14° to 5°C (Nisbet 1989). Nisbet also makes the extreme assumption that hydrates are very close to the surface in the Arctic Islands (as close as 50 m). These assumptions lead to a very high release rate per unit area. However, in this scenario, Nisbet applies this release rate to only a small part of the total continental hydrate area--for a total emission estimate of at least 100 Tg/yr. It is not clear whether the other hydrate areas are not destabilized, or if the scenario is simply not intended to give a global picture. If, for example, the areal release rate is applied to the affected area used in Bell's scenario, the annual emissions from this scenario would be about 10,000 Tg CH_4/yr. In a related paper, Nisbet contends that hydrates do not exist in all areas of hydrate stability, but only where the surface rocks are sedimentary -- suggesting that the total affected area would be less than the area used by other researchers (Nisbet and Ingham, submitted). Finally, Nisbet suggests that global warming will be transmitted to the hydrate zone in thermal pulses, rather than as a steady process. These thermal pulses could result in (1) occasional bursts of methane, as a result of the rupture of hydrate-trapped gas pools, and (2) slow methane seepage to the surface as hydrates decompose (Nisbet and Ingham, submitted) (see Exhibit 3-5).

Oceanic Hydrate Scenarios

Scenarios of methane emissions from oceanic gas hydrates have been devised by three different researchers, and are presented below.

Kvenvolden's Scenario: > 150 Tg CH_4/yr

To place an upper limit on methane emissions from oceanic hydrates, Kvenvolden makes the rough estimation that a rise in global temperature will destabilize oceanic reserves after thousands of years. This will result in methane emissions that could exceed his estimate of emissions from the continental shelf (previously estimated to be 150 Tg CH_4/yr). Kvenvolden does not provide a more specific estimate of oceanic hydrate emissions (Kvenvolden 1991e) (see Exhibit 3-4).

Bell's Scenario: 160 Tg CH_4/yr

Bell (1982) assumes that, as a result of global warming, the surface water temperature of the Norwegian Sea, which feeds the Arctic Ocean, will rise about 3.5°C (reflecting a similar change in air temperature). When this water enters the Arctic, it descends to the "intermediate" depth of 250-350 m. The predicted increase in precipitation in the Arctic region will increase the extent of mixing with the water entering from the Norwegian Sea. This warmer, "intermediate" water will extend about halfway around the Arctic Basin. Thus, the temperature along half the length of the 300 m depth contour in the Arctic Ocean will increase from -0.5° to 3°C. Given this temperature change, the hydrates extending from the ocean sediment interface to a depth of 40 m below the sea floor will be destabilized where ocean depths are between 280 and 370 m. Bell estimates that the methane in this 40 m zone, which represents about 1% of the oceanic methane hydrate reserves, will be entirely and uniformly released over a 100 year span. To estimate global annual emissions from this release, Bell assumes that a global oceanic methane reserve of 13 million Tg is uniformly distributed in the top 250 m of ocean sediments, at depths between 200 and 1,000 m (see Exhibit 3-4).

Revelle's Scenario: 640 Tg CH_4/yr

In this scenario, Revelle (1983) assumes that the mean annual air temperature increases 3°C globally, and that ocean surface temperatures rise by the same amount. Advection and eddy currents will carry the heat downward, and bottom water temperatures will eventually rise 1° to 4°C. As a result, the minimum depth of hydrate stability will increase about 100 m at all latitudes, destabilizing the top 100 meters of the hydrate layer throughout the world. Revelle assumes that (1) hydrates are evenly distributed within the hydrate zone, and (2) that 20% of the released methane will be absorbed by the water in the pores of the ocean-bottom sediment before it can reach the atmosphere. He calculates that after approximately 100 years, oceanic methane hydrates will begin emitting methane at an annual rate of 640 Tg. Due to its magnitude, this feedback alone could result in as much as 2°C of additional global warming (Revelle 1983) (see Exhibit 3-4).

Composite Scenarios

It is difficult to compare these scenarios because they are based on different assumptions of the expected temperature rise and of the size of hydrate reserves. To normalize the assumptions about temperature rise and hydrate reserves across all scenarios, an "emission factor" is calculated here for each scenario:

Exhibit 3-4

Oceanic Hydrate Scenarios

	Kvenvolden	Revelle	Bell	Composite
Air Temperature Rise (°C)	3*	3	3 - 4	3
Methane Reserves (Tg)	$1x10^7$	$1.8x10^7$	$1.3x10^7$	$1x10^7$
% of Area/Reserves Destabilized		13%	1%	
Destabilized Area (m^2)		$1.9x10^{12}$	$1.2x10^{11}$	
Time Until Destab. Begins (yrs)	1000's	100	100's	
Time to Fully Destabilize (yrs)	1000's		100	
Efficiency of Escape to Atmosphere	100%	80%	100%	100%
Emission Factor (yr^{-1} $°C^{-1}$)	$5.0x10^{-6}$	$1.2x10^{-5}$	$3.4x10^{-6}$	$6.7x10^{-6}$
Annual Emissions (Tg/yr)	**>150**	**640**	**160**	**200**

*This value was not provided by the researcher and was assumed to be equal to the composite scenario value.

The emission factors for the above scenarios are presented in Exhibits 3-4 and 3-5, along with average emission factors for all oceanic and continental scenarios. There appears to be general agreement regarding these factors, within an order of magnitude. The existing difference in emission factors primarily represents different conceptions of the thermal conductivity of sediment and of the percentage of total hydrates that will be affected by global warming.

The average emission factors can be applied to the current "best estimates" of temperature rise and hydrate reserves to arrive at composite, or best-estimate, scenarios. In the oceanic composite scenario, the temperature rise is assumed to be equal to the midpoint of the IPCC global prediction (3°C), since oceanic hydrates are globally distributed. For the continental composite scenario, the temperature rise is assumed to be equal to the average IPCC prediction for the polar regions (6°C), since continental hydrates exist only at high latitudes. The total reserves are assumed to be equal to the latest estimates provided by Kvenvolden ($1x10^7$ Tg for oceanic, $5x10^5$ Tg for continental).

The composite scenarios predict annual emissions of about 200 Tg CH_4/yr from oceanic hydrates and about 100 Tg CH_4/yr from continental hydrates with a range of uncertainty of at least one order of magnitude. These composite scenarios are intended to provide a rough, average estimate of the magnitude of hydrate releases. However, some of the emission factors in the researchers' scenarios are intentionally extreme. On the other hand, the temperature rise and reserve estimates assumed in the composites are not intended to be extreme, but do encompass a large degree of uncertainty. The annual emissions predicted by the composites could be orders of magnitude larger or smaller depending on the temperature rise and reserve assumptions used.

It should also be noted that the composite scenarios assume that the efficiency of escape to the atmosphere is 100%. This assumption is made because only one of the seven hydrate release scenarios mentions that the rate of absorption or oxidation is not 100%. However, there is reason to believe that efficiency could be less than 100% (see section 3.3). Therefore, this is somewhat of an extreme assumption because efficiency can not be more than 100% but could be much less than 100%.

Exhibit 3-5

Continental Hydrate Scenarios

	Kvenvolden (offshore)	Kvenvolden (onshore)	MacDonald	Bell	Nisbet	Composite
Air Temperature Rise (°C)	6*	6*	2	10	19	6
Methane Reserves (Tg)	$1.5x10^5$	$3.5x10^5$	$5.3x10^5$	$2.7x10^6$	$5x10^5$*	$5x10^5$
% of Area/Reserves Destabilized			100%	50%		
Destabilized Area (m²)				$6.5x10^{12}$	$1.0x10^{11}$	
Time Until Destab. Begins (yrs)	100's	1000's	100	100's	100-200	
Time to Fully Destabilize (yrs)	1000's	1000's	10,000	4000		
Efficiency of Escape to Atmosphere	100%	100%	100%	100%	100%	100%
Emission Factor (yr^{-1} $°C^{-1}$)	$5x10^{-5}$		$4.7x10^{-5}$	$1.3x10^{-5}$	$1.1x10^{-5}$	$3.3x10^{-5}$
Annual Emissions (Tg/yr)	**50**	**100**	**50**	**300**	**220**	**100**

*These values were not provided by the researchers and were assumed to be equal to the composite scenario values.

3.2 Permafrost

Permafrost is ground that remains at or below 0°C throughout the year for at least two consecutive years, and usually contains ice held within soil pores. Methane can occur in permafrost in ice, peat, loess, and any material that is perennially frozen. It is believed that some, if not all, permafrost contains trapped methane. While little research has been done on the subject of fossil emissions of methane from permafrost, this is a significant, potential source of atmospheric methane in the future.

Permafrost methane is not the same as methane hydrates. Permafrost methane is methane with the standard molecular structure that is trapped within permafrost. Methane present where the hydrate stability zone overlaps with the permafrost zone (see exhibit 3-3), exists in the form of methane hydrate, and is not considered permafrost methane.

3.2.1 Background

To draw reasonable conclusions about methane emissions from permafrost, it is important to understand the following characteristics of permafrost:

- The amount of methane in permafrost
- The rate at which permafrost is melting now and can be expected to melt in the future
- The total area of permafrost subject to melting
- How much of the methane released from permafrost can be expected to reach the atmosphere.

These characteristics are discussed below.

Methane Concentration and Total Reserves

Methane concentration is the weight of methane per unit weight of permafrost. Kvenvolden (1991d) has measured the methane content of shallow permafrost cores from three sites on the campus of the University of Alaska, Fairbanks. Methane concentration was highly variable, ranging from 0.00032 to 22 mg CH_4 per kg of sample. Core samples taken from a permafrost tunnel excavated by the U.S. Army Corps of Engineers at a site 16 km north of Fairbanks, Alaska, contained 0.0008 to 6.6 mg CH_4 per kg of sample (Kvenvolden 1992). The number of samples analyzed in both of these experiments was fairly small, and the average concentration is still uncertain.

A preliminary estimate of partial reserves of methane in permafrost can be extrapolated from the known volume of ice in permafrost. There are approximately 250,000 km^3 of ice worldwide, of which 80% is ground ice within permafrost (Michael Smith, pers. comm. 1992). The total mass of permafrost ice is then 2.5×10^{17} kg. Applying the above concentration estimates to this estimate of the volume of permafrost ice results in a range for partial methane reserves of 0.08 to 5,500 Tg CH_4. Additional methane reserves could exist in the non-ice portions of permafrost, the total mass of which is not known at this time.

Destabilization Rate

The destabilization rate is the rate at which permafrost melts, usually expressed as downward distance from the top edge of the permafrost per unit time. Permafrost is stable where the mean annual surface temperature (MAST) is less than 0°C. Permafrost stability is also related to vegetation, seasonal snow cover, geological setting, and topography. Osterkamp postulates that when MAST rises above 0°C, Alaskan permafrost typically melts at a rate of 10-20 cm/yr, while the time to achieve a new equilibrium thickness can be less than one hundred years or more than ten thousand years (Osterkamp, submitted).

Destabilization Area

The destabilization area is the areal extent of permafrost subject to destabilization, and is a subset of the total area of permafrost. Permafrost exists beneath approximately one quarter of the land area of the earth, or 3.6×10^{13} m^2 (Michael Smith, pers. comm. 1992).

Efficiency

Efficiency refers to the percentage of methane released from permafrost that actually reaches the atmosphere, as opposed to being oxidized, in the active soil layer. The most critical factor affecting permafrost methane emissions will likely be the oxidation rate of permafrost methane as it makes its way through the active soil layer.

While no research has been published on the efficiency of methane escaping from melting permafrost, studies of methane released from other sources (e.g., landfills, wetlands) suggests that oxidation rates can be very high (Whalen et al. 1990). By measuring methane concentrations in pore water and atmospheric emissions from northern wetlands, it has been demonstrated that the vast majority of methane produced in relatively well-drained soils is consumed before it reaches the atmosphere (Whalen and Reeburgh 1992). On the other hand, participants at the workshop held at Oak Ridge (see section 2.5.3) hypothesized that permafrost methane "should readily escape [to the atmosphere] if permafrost melts" (Post 1990).

The largest single determining factor of oxidation rate is soil moisture. However, conflicting hypothesis exist for how oxidation will be affected by soil moisture. For example, some researchers contend that if the soil is completely inundated (the water table is at or above the soil surface) then the released methane is likely to pass through this layer and reach the atmosphere (high efficiency). Others contend that "if the active soil layer becomes wetter then the rate of methane transport through it will be slowed and the probability of oxidation could increase, assuming the soil does not become so wet that it goes anaerobic" (Mulkey, pers. comm. 1993).

In a drier scenario it has been suggested that if a well-drained layer exists, even as little as a few centimeters, then conditions are ripe for oxidation, and some or all of the released methane could be oxidized in this zone (low efficiency) (Bartlett, pers. comm. 1993). It has also been suggested that "if the soil becomes drier then the rate of transport should be increased and emissions could become more likely, particularly if the active layer becomes so dry that bacterial growth is inhibited" (Mulkey, pers. comm. 1993).

3.2.2 Current Emissions

The factors described above can be combined to quantitatively calculate current and future emissions as follows:

emissions = (concentration) x (destabilized area) x (destabilization rate) x (efficiency)

Unfortunately, there is insufficient information at this time to apply this formula to current or future emissions. Information does exist, however, to allow the formation of some general hypotheses about permafrost methane emissions.

Evidence exists to suggest that temperature in the polar regions has already risen considerably since pre-industrial times, and that permafrost is melting and releasing methane. A detailed analysis of sub-surface temperature records from wells drilled in Alaska indicates that the permafrost surface temperature has risen by 2° to 4°C over the past century (Lachenbruch and Marshall 1986). Furthermore, some discontinuous areas of permafrost in Alaska are known to be melting at this time (Osterkamp 1983). No estimates are available as to what quantity of permafrost is melting, or how much methane is being liberated in this process.

3.2.3 Future Emissions

Permafrost will be destabilized by global warming in the future as a result of expected increases in temperature. While the relationship between permafrost temperature and surface temperature is not well defined, it has been hypothesized that if global temperatures increase by only 1 °C, then permafrost will melt entirely in 8% to 20% of the current permafrost area, and it will recede by an average of 0.5 m in the remaining area (Osterkamp, pers. comm. 1992). With a temperature increase of 2°C, 20% to 40% of the permafrost area will be lost, and the top 1 m of permafrost will melt in the remaining areas (Osterkamp, pers. comm. 1992). However, there may be some counteracting effects. For example, an increase in snow cover could reduce the above predictions by as much as 50% (IPCC 1990).

Methane will be released as permafrost melts due to climate change. The amount of methane that will be liberated, and how much of this will actually reach the atmosphere, is not known. Currently, no scenarios exist in the literature for future emissions from permafrost. Preliminary results from Khalil's ongoing study of potential permafrost emissions show that as much as 60 Tg CH_4 per year could be released to the atmosphere by the end of the next century (M.A.K. Khalil, pers. comm. 1992).

3.3 Uncertainty / Further Research

Knowledge of natural methane emissions from fossil sources is limited. Therefore, a large degree of uncertainty must be attached to future emission scenarios. The uncertainty could be partially resolved with additional research. Uncertainty exists in the following areas:

Methane Reserve Estimates

The total quantity of methane currently stored in the form of gas hydrates or permafrost methane is not well known.

Gas Hydrates

Estimates of the exact quantity of methane hydrate reserves vary by over three orders of magnitude for oceanic hydrates and by two orders of magnitude for continental hydrates. While recent, independent estimates agree on the values provided by Kvenvolden (1991e), these estimates are still highly uncertain. An extensive program of sediment sampling on continental slopes and in permafrost regions worldwide, to determine hydrate depth, thickness, distribution, and methane concentration could considerably reduce this uncertainty.

Permafrost

Very few samples of permafrost have been tested for methane concentration, and all of these have been from a very small geographic area around Fairbanks, Alaska. A much more intensive and geographically diverse permafrost sampling program is needed. Also, a methodology must be devised for estimating the global volume of permafrost, and not just permafrost ice.

Hydrate Distribution

In general, the scenarios for gas hydrates presented above assume that hydrate reserves are uniformly distributed within the hydrate zone. However, this assumption is not well substantiated. Kvenvolden (1988) points to exploratory drilling results from Prudhoe Bay and the coast of Guatemala as evidence that "hydrates are present in discrete layers and occupy only a small part of the potential field of gas hydrate stability." If hydrates are not prevalent throughout the projected zones of destabilization, the scenarios may overstate the potential from this source. However, if the hydrates are discontinuous but fairly evenly distributed by depth and latitude, the scenarios may be accurate. A program of sediment sampling will help resolve this issue.

Thermal Conductivity

Thermal conductivity (the ability of the water/soil column to transmit changes in surface temperature) will determine the rate at which surface warming is conducted to, and through, the hydrate and permafrost zones. Thus, thermal properties of water and soil will affect not only the time lag before destabilization begins, but also how fast destabilization will take place--the annual emission rate. However, thermal properties should affect only the time frames involved before a new equilibrium stability is reached--not the total magnitude of destabilization.

Gas Hydrates

In the oceanic hydrate case, thermal conductivity is determined not only by the thermal properties of seawater and sub-ocean sediment, but also by ocean mixing, which can be highly variable and difficult to determine. For example, in Bell's oceanic scenario, global atmospheric temperature rise rapidly affects (over a span of about 100 years) the bottom temperature of the Arctic Ocean at a depth of 300 m. This rapid translation of surface warming is based on assumptions of water circulation patterns. According to Kvenvolden (1988), however, this scenario overestimates the degree of mixing between the Arctic Ocean and the Canada Basin and, thus, the time delay before the Arctic Ocean bottom temperature would rise. Ocean circulation patterns must be more clearly understood to resolve this uncertainty.

Thermal conductivity is better understood in the continental hydrate case than in the oceanic case, but it is still difficult to model. Conductivity depends on soil porosity, conductivity of soil grains, and whether the soil is frozen or thawed. Determining these conditions can be difficult. For instance, even below 0°C, sediment may not be frozen, due to surface effects that are not well understood at this time (MacDonald 1990). Furthermore, different amounts of energy are required to melt ice and hydrate. Movement of the ice/hydrate boundary, therefore, complicates the calculation of thermal conductivity.

Due to the wide range of possible conditions for thermal conductivity, some researchers have concluded that huge annual methane hydrate emissions are possible within a century, and others have concluded that annual emissions will be relatively small and will only begin to take place after thousands of years. It is generally agreed, however, that the methane hydrate reserves with the shortest lag time before destabilization begins are the offshore continental shelf reserves (Kvenvolden 1991e; Lashof, pers. comm.).

Permafrost

The time lag before temperature rise reaches permafrost methane is both much shorter and more certain than for gas hydrates because permafrost exists much closer to the surface, and there is less room for variability. However, understanding of the rate of permafrost destabilization is still limited. Further research on the current distribution of permafrost surface temperatures and how these relate to air temperatures is necessary to make a realistic assessment of the effects of a given increase in air temperature on permafrost stability (Osterkamp, pers. comm. 1992).

Methane Oxidation / Absorption

Another potentially mitigating factor for both the permafrost and gas-hydrate scenarios is the amount of escaping methane that will either be absorbed by the water in the pores of the surrounding sediment, or oxidized in the water column, or the active soil layer, before it reaches the atmosphere. Absorption means that the methane becomes dissolved in water or trapped in soil and can eventually come out of solution and reach the atmosphere. Revelle assumes that 20% of the methane released from oceanic hydrates is trapped in sediment before it reaches the ocean.

Methane is oxidized when it reacts with oxygen in soil or water and is converted to carbon dioxide and water. For terrestrial hydrates, the rate of oxidation depends primarily on soil moisture, precipitation, and soil porosity. No estimates have been made for the percentage of methane released from continental hydrates that will be oxidized. Oxidation of oceanic hydrate methane depends on the oxygen content of the water. Little information is known about the rate of oxidation of methane from hydrates in the water column, but Revelle (1983) contends that all methane that escapes from the sea floor sediment "should rise rapidly to the sea surface before it can be oxidized in the water". Other hydrate modelers make the assumption, perhaps arbitrarily, that released methane is neither trapped nor oxidized in sediment or the water column, but escapes to the atmosphere.

Studies of methane released from non-hydrate sources show that oxidation in both soil and water columns is very significant. Research has shown that much of the methane generated in landfills and wetlands can be oxidized in the soil column (Whalen et al. 1990; Whalen and Reeburgh 1992). Similarly, geochemical studies have shown that dissolved methane, emanating for example from hydrothermal vents, is rapidly oxidized in the water column by bacteria (Mulkey, pers. comm. 1993). Whether methane released from hydrates or permafrost will experience similar oxidation rates to these other sources is not known and therefore needs to be researched. While it may be possible to design experiments that would help resolve this uncertainty, it is also possible that methane will be released from hydrates in the future on such a large scale that there is no reliable way of predicting the oxidation processes that would be involved.

CHAPTER 4

SUMMARY AND CONCLUSIONS

Current emissions from natural wetlands have been reasonably well quantified, and experts have agreed on annual emissions of approximately 109 Tg of methane, with an estimated range of 70 to 170 Tg of methane per year. Emissions from fossil sources are less well known, but probably contribute only marginally to atmospheric methane at the present time.

It is difficult to predict future methane emissions from natural sources or to assess the potential positive feedback contribution of methane emissions from natural sources to the climate system. However, experts in this field have attempted to estimate the amount of methane that might be expected from these sources and over what time periods these changes may occur, assuming that current trends in energy use and agricultural activities continue. The IPCC predictions of global warming are used as standard assumptions for these "best guesses" (see Exhibit 4-1).

In order to predict future methane emissions from wetlands, researchers have attempted to quantify the relationship between wetland emissions and the environmental variables that will be affected by climate change. Relationships have been hypothesized between emissions and temperature, precipitation as it affects inundation, and plant species and growth rates. Rough methods of calculating future emissions based on these relationships have been developed for northern wetlands, but are difficult to discern from the limited and highly variable data available from tropical wetlands.

Given the relationships between methane emissions from wetlands and environmental variables, researchers have concluded that it is unlikely that emissions will decrease as a result of climate change over the next century, instead, wetland emissions will probably increase. Quantitative predictions of potential emissions increases for northern wetlands, based on three scenarios of climate change, range widely from 5 Tg/year to 290 Tg/year.

The rise in methane emissions from wetlands would take place roughly concurrently with climate change. Fast and slow mechanisms have been identified by which climate change will alter methane emissions. For example, the emission rate of a particular wetlands ecosystem will be affected immediately by climate change, while the areal extent and plant community will be affected gradually, over decades. According to these mechanisms, methane emissions from wetlands will likely reach the predicted increased levels within the next century.

By all accounts, fossil sources could release tremendous quantities of methane, some of which could reach the atmosphere. These emissions could amount to hundreds of teragrams annually from hydrates, and 60 Tg/yr from permafrost. However, the timing of these fossil emissions is highly uncertain. While permafrost emissions could occur within a century, major hydrate emissions are not likely to take place for at least one to several hundred years, and may not occur at all within the next few thousand years. Importantly, even though these emissions may not occur for many years, they would still be a result of current day activities and their related emissions of greenhouse gases.

Exhibit 4-1

Potential Increases in Methane Emissions from Selected Natural Systems due to Climate Change

System	Current Emissions ($Tg\ CH_4/yr$) estimate	Current Emissions ($Tg\ CH_4/yr$) range	Range of Predicted Increases ($Tg\ CH_4/yr$) within 100 yrs	Range of Predicted Increases ($Tg\ CH_4/yr$) after 100 yrs
Tropical Wetlands	66	34 - 118	0[1]	0[1]
Temperate Wetlands	5	n/a	0[1]	0[1]
Northern Wetlands	38	29 - 52	5 - 290	5 - 290
Hydrates (Continental)	5	0-5	0[2]	50 - 300[2]
Hydrates (Oceanic)	0	0	0[2]	150 - 640[2]
Permafrost	0	0	0 - 60[2]	0 - 60[2]
Total	114	70 - 175	5 - 370	200 - 1300

[1] In the absence of future predictions for these systems, they are assumed here to remain constant.
[2] The predicted increases for hydrates and permafrost are relatively more uncertain than the predicted increases for wetlands.

To summarize, while future emissions predictions are highly uncertain, especially for fossil sources, available information indicates that methane emissions from all natural sources could increase by 5 to 370 Tg/year within the next century. This increase would be primarily from wetlands and permafrost, which respond to climate change more quickly than gas hydrates. The methane from such an increase is equivalent to about 100 to 7,000 million metric tons of CO_2 per year, or an additional 0.2% to 17% of carbon dioxide beyond current predictions for the year 2100. In the centuries to follow the next one, methane emissions from natural sources could rise further as gas hydrates are slowly destabilized.

With additional research, scientists will be able to more confidently predict future natural source emissions. For wetlands, additional multi-year flux studies and additional work in more geographical areas will reduce the uncertainty surrounding current emission estimates, and improve understanding of the relationships between methane and environmental variables. More complex wetland models need to be developed as well, incorporating as many climate variables as possible. Future predictions can only be accurate if they are based on correct assumptions of climate change. Therefore, further efforts to increase the accuracy and resolution of general circulation models will also improve natural methane emissions projections.

Scientists have only recently begun to investigate the potential of gas hydrates and permafrost methane to contribute to global warming. As this field is more thoroughly explored, a more accurate picture will develop. This process will require improved estimates of the magnitude and distribution of hydrate and permafrost methane reserves, as well as a greater understanding of the thermal properties of permafrost and of the ocean waters and soil layers in the vicinity of hydrates. Even if these issues are resolved, it may not be possible to determine what percentage of released methane will actually reach the atmosphere until large, fossil-source emissions are in progress.

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APPENDICES

Appendix A: List of UNH Workshop Participants

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Appendix B: Methane Flux from Tropical Wetlands

(Fluxes made using enclosure techniques unless otherwise noted; Flux units are $mgCH_4/m^2/d$)

HABITAT	LATITUDE	AVG. FLUX	ANNUAL FLUX ($g/m^2/yr$)	N	RANGE	SITE	MEAS. PERIOD	REF.
Open water Non-forest swamps Flooded forests	3° 3° 3°	88[1] 390[1] 75[1]	- - -	36 25 16	0.5-665 0.8-1976 1-533	Amazon flood plain	July (falling high water)	1
Open water Non-forest swamps Flooded forests	3° 3° 3°	27 230 192	- - -	41 90 55	-10.5-111 0-1224 0-2997	Central Amazon flood-plain	July-Sept. (high water)	2
Open water Non-forest swamps Flooded forests	3° 3° 3°	74 201 126	- - -	116 85 58	0-1160 -11.3-1600 0-840	Amazon flood-plain	Apr.-May (rising high water)	3
Open water Non-forest swamps Flooded forests	3° 3° 3°	40 131 7.1	- - -	40 31 11	- - -	Amazon flood plain	Nov.-Dec. (low water)	4
Open water Non-forest swamps Flooded forests	3° 3° 3°	44 214 150	16[2] 78[2] 55[2]	90 63 31	0-350 0-2600 0-2700	Lakes near Manaus	Annual	
Open water Non-forest swamps Flooded forests	3° 3° 3°	36 35 75	13[2] - -	- - -	- - -	Lake near Manaus	Annual Feb-Aug Feb-Aug	5
Lakes (w/ macrophytes)- Open water Non-forest swamps Flooded forests	9° 9° 9°	7.5 29.6 257.6	- - -	26 16 18	0-48 0-132 0-1872	Orinoco flood-plain	July-Oct. (high water)	6
Lakes (w/o macrophytes)- Open water Flooded forests	9° 9°	73.8 307.2	- -	14 8	2-530 3-2288	Orinoco flood-plain	July-Oct. (high water)	
Lake 1 (w/ macrophytes)- Open water Non-forest swamps Flooded forests	9° 9° 9°	22.6 61.3 174.4	- - -	30 37 24	1-159 -4-918 0-1648	Orinoco flood-plain	July-Dec.	

HABITAT	LATITUDE	AVG. FLUX	ANNUAL FLUX (g/m^2/yr)	N	RANGE	SITE	MEAS. PERIOD	REF
Lake 2 (w/o macrophytes)-								
Open water	9°	32.6	-	57	0-587	Orinoco flood-plain	July-Dec.	
Flooded forest	9°	248	-	19	0-2736			
Flooded forest-								
Flooded soils	1°	106	-	11	9.9-550	Congo River basin	Feb. & Oct.	7
Wet/moist soils	1°	4.9	-	4	1.2-7.6			
Dry soils	1°	-1.9	-	5	-0.8-4.6			
Open water-								
Shallow (0.5-2m)	9°	967[3]	-	15[4]	297-3635	Gatun Lake, Panama	Feb.-Oct.	8
Middle (4-6m)	9°	395[3]	-	15[4]	127-1148			
Deep (7-10m)	9°	54[3]	-	6[4]	0-207			
Swamp-								
Well-drained (rain forest)	9°	0.71	0.26[2]	144	-2-13	Mojinga Swamp, Panama	Annual	8
Marsh	9°	379	138[2]	36	0-2600			
Swamp forest	9°	346	126[2]	90	0-2200			

[1] Corrected from original data due to 37% error in bubble flux. See Bartlett et al. (1990).

[2] Annual flux is average flux multiplied by 365 days.

[3] Bubble flux only; more than 97% of total flux.

[4] 24-hour flux measurements rather than short-term (15-30 minutes).

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Appendix C: Methane Flux from Temperate and Subtropical Wetlands
(Fluxes made using enclosure techniques unless otherwise noted; Flux units are $mgCH_4/m^2/d$)

HABITAT	LATITUDE	AVG. FLUX	ANNUAL FLUX ($g/m^2/yr$)	N	RANGE	SITE	MEAS. PERIOD	REF.
Salt marsh- short S.alter- niflora	31°	145	53.1	17	0.24-1920	Sapelo Isl., GA	annual	1
tall S.alter- niflora	"	15.8/ 1.2	0.4	19	0.02-144	"		
Salt marsh- short S.alter- niflora	37°	3.0	1.3	24	0-13.9	Bay Tree, VA	annual	2
tall S.alter- niflora	"	5.0	1.2	29	-1.1-16.2	"		
salt meadow	"	2.0	0.43	47	-2.7-21.3	"		
short S.alter- niflora	39°	0.5	-	6	-1.0-3.9	Lewes, DE	June	
short S.alter- niflora	38°	-0.8	-	4	-1.7-0	Wallops Isl., VA	June	
tall S.alter- niflora	"	1.5	-	3	1.2-1.7	"		
salt meadow	"	-1.9	-	2	-1.8- -2.0	"		
high marsh	33°	1.5	-	25	-3.9-9.6	George- town, SC	Apr & Aug	
tall S. alter- niflora	"	0.4	-	8	0-4.8	"		
short S. alter- niflora	38°	13.4	-	3	2.2-19.2	Sapelo Isl., GA	Nov	
Juncus roemer- ianus	30°	3.9	-	9	-3.2-6.3	Panacea, FL	Sept- Dec	
short S. alter- niflora	"	0.6	-	2	0-1.3	"		
Salt marsh- short S. alter- niflora	41°	4.5[1]	1.6	24	1.3-12	Sippiwis- sett, MA	annual	3
Graminoid marshes- Saline	30°	15.7	5.7	36	1.3-48	Miss. Delta, LA	annual	4

HABITAT	LATITUDE	AVG. FLUX	ANNUAL FLUX ($g/m^2/yr$)	N	RANGE	SITE	MEAS. PERIOD	REF.
Brackish	"	267	97	36	13-1300	"		
Fresh	"	587	213	27	0-2600	"		
Open water-Saline	"	4.8	1.7	13	-	"		
Brackish	"	17	6.2	13	-	"		
Fresh	"	49	18.2	13	-	"		
Graminoid marsh-Saline	37°	16	5.6	21	1-46	Queen's Creek, VA	annual	5
Brackish	"	64.6	22.4	21	1.3-180	"		
Brackish/Fresh	"	53.5	18.2	21	-3-259	"		
Ombrotrophic bog	39°	-1.14	-	105	-6.7-29.6	Buckle's Bog, MD	annual	6
Minerotrophic fen (5 sites)	"	3.56	-	527	-7.7-748	Big Run Bog, WV		
Beaver pond	"	250	-	105	1-1400	"		
Running stream	"	300	-	105	2-4000	"		
Minerotrophic fen-1989-1990	43°	133	49	38	7-941	Sallie's Fen, NH	annual	7
1990-1991	43°	291	107	107	5-3563	"		
Forested swamp-swamp bank	37°	117	43.7	29	0-475	Newport News Swamp, VA	annual	8
Peltandra	37°	155	41.7	29	4-469	"		
Smartweed	"	83	"	29	0-405	"		
Ash tree	"	152	"	29	0-1005	"		
Swamp	42°	356[2]	-	7	120-160	S.E. Mich.	May-Sept	9
Farm ponds	"	440[2]	-	25	92-1100	"		
Maple/gum swamp	36°	-	0.5	37	-6-20	Dismal Swamp, VA	annual	10
Cypress swamp-floodplain	33°	9.9	-	6	4.6-21.8	Four Holes Swamp, SC	June	11

HABITAT	LATITUDE	AVG. FLUX	ANNUAL FLUX (g/m^2/yr)	N	RANGE	SITE	MEAS. PERIOD	REF.
deep-water	31°	92.3	-	3	10-256	Okefen-okee Swamp, GA		
flowing water	26°	67.0	-	6	8.2-265	Cork-screw Swamp, FL		
Bottomland hardwoods & gum - cypress swamps	32°	-	10-34	-	-10-361	Ogeechee River, GA	annual (multi-yr)	12
Shrub swamp	31°	149	-	42	-7.5-1250	Okefen-okee Swamp, GA	annual	13
Aquatics/Prairie	31°	130.4	-	50	-7.9-1000	Okefen-okee Swamp, GA	annual	
Cypress swamp	"	39.8	-	47	-10-442	"		
Gum/Bay swamp	"	69.6	-	14	-7.5-293	"		
Lakes	"	115.9	-	7	30.8-217	"		
Wet prairie/ Sawgrass	26°	61	-	122	0-624	Ever-glades, FL	annual	14
Wetland forest	"	59	-	22	-3-274	"		
Salt water mangroves	"	4	-	17	1.9-7.7	"		
Impoundments/disturbed wetlands	"	74	-	32	5.9-198	"		
Hardwood hammock	26°	0	-	3	-	Ever-glades, FL	Dec-Feb	15
Red mangroves	"	4.2	-	17	-	"		
Dwarf cypress/ sawgrass	"	7.5	-	25	-	"		
Spikerush	"	29.4	-	7	-	"		
Sawgrass <1m	"	38.8	-	62	-	"		

HABITAT	LATITUDE	AVG. FLUX	ANNUAL FLUX ($g/m^2/yr$)	N	RANGE	SITE	MEAS. PERIOD	REF.
Sawgrass/Spike-rush/Periphyton	"	45.1	-	8	-	"		
Swamp forest	"	68.9	-	13	-	"		
Sawgrass >1m	"	71.9	-	24	-	"		
Dwarf red mangrove	"	81.9		19	-	"		
Sawgrass/Muhly grass/Periphyton	26°	88[3]	-	6	-	Everglades, FL	annual	16
Tall sawgrass/ Muhly grass	"	7.9[3]	-	7	-	"		
Mangroves	"	82[3]	-	4	-	"		
Forested swamp	28°	113[3]	-	12	-	Tampa Bay, FL		
Subtropical estuary	"	2.6[3]	-	80	-	"		
Sawgrass	26°	107	-	60	9-2387	Everglades, FL	annual	17
Pond open water	"	624	-	9	11-2646	"		

[1] Measured from cores.
[2] Bubble flux only.
[3] Diffusive flux only, calculated from surface water concentration data.

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Appendix D: Methane Flux Measurements from Northern Wetlands
(Fluxes made using enclosure techniques unless
otherwise noted; Flux units are $CH_4/m^2/d$)

ARCTIC

HABITAT	LATITUDE	AVG. FLUX	ANNUAL FLUX ($g/m^2/yr$)	N	RANGE	SITE	MEAS. PERIOD	REF.
Subarctic mire: ombrotrophic	68°	11.6	0.13	95	0.3-29	Stordalen, Sweden	June-Sept.	1,2
intermediate	"	58	1.44	25	8.6-112			
minerotrophic	"	360	30.5	20	80-950			
Wet coastal tundra	63-70°	119	-	44	34-266	Alaska North Slope & Denali	Aug.	3
Moist tundra	"	4.9	-	12	0.3-12			
Meadow tundra	"	40	-	14	9-77			
Alpine fen	"	289	-	6	244-344			
Boreal marsh	"	106	-	7	86-122			
Tussock tundra composite (1987)	65°	22.4	-	-	-	Alaska, Fairbanks	Annual	4,5
Wet meadow composite (1987)	"	32.2	-	-	-			
Moss (1987)	"	0.9	0.5	46	0-17			
Moss (1988)	65°	10.1	4.4	57	0-146			
Moss (1989)	"	29	4.8	58	0-367			
Moss (1990)	"	3.8	0.5	51	0-26			
Intertussock (1987)	"	2.8	0.6	39	0-34			
Intertussock (1988)	"	25.2	3.9	54	0-292			
Intertussock (1989)	"	12.4	4.3	57	0-145			
Intertussock (1990)	"	5.9	0.8	51	0-57			

HABITAT	LATITUDE	AVG. FLUX	ANNUAL FLUX (g/m^2/yr)	N	RANGE	SITE	MEAS. PERIOD	REF.
Carex sedge (1987)	"	33.5	4.9	33	<1-105			
Carex sedge (1988)	"	3.2	0.8	57	0-12			
Carex sedge (1989)	"	23	4.3	60	0-104			
Carex sedge (1990)	"	451.9	60.6	51	0-2216			
Eriophorum tussocks (1987)	"	29.5	8	48	0-167			
Tussocks (1988)	"	60.8	11.4	57	0-653			
Tussocks (1989)	"	48.8	8.1	60	0-445			
Tussocks (1990)	"	96.8	13.6	51	0-302			
Lakes & ponds	66-70°	21	-	6	4.6-131	Alaska, North Slope	July-Aug.	6
Alpine tundra	"	0.6	-	8	-0.2-6.3			
Moist tundra	"	31	-	42	0-159			
Wet tundra	"	90	-	18	0-265			
Low brush-Muskeg bog	"	45	-	6	12-101			
Spruce forest	"	4.6	-	18	-0.3-67			
Meadow & tussock tundras	68-70°	30	-	27	-1-145	Alaska, N.Slope & Foot-hills	Aug.	7
Tussock tundra: tussocks	69°	3.4	-	6	-	Alaska, N.Slope	Aug.	8
intertussocks	"	2.9	-	8	-			
Meadow tundra	"	64.4	-	23	-			
Lakes & ponds	"	37.5	-	31	-			
High centered polygons	"	4.9	-	5	-			
Low centered polygons: troughs	"	61.9	-	10	-			
basins	"	46.1	-	24	-			

HABITAT	LATITUDE	AVG. FLUX	ANNUAL FLUX (g/m^2/yr)	N	RANGE	SITE	MEAS. PERIOD	REF.
rims	"	12.1	-	15	-			
Wet tundra	69°	100.1	-		-	Alaska, N.Slope	Aug.	9
Very wet tundra	"	253.9	-		-			
(Calc. regional mean, 1987)+	"	17.3						
Wet meadow tundra	61°	144	-	73	16-426	Alaska, Yukon Kuskokwim Delta	July-Aug.	10
Upland tundra	"	2.3	-	82	-2.1-18			
Large lakes*	"	3.8	-	12	-			
Small lakes*	"	77	-	32	-			
Lake vegetation	"	89	-	51	63-154			
(Calc.regional mean)+	"	48.5						
Small lakes-bubbles(calc.)	61°	112	-	-	-	Alaska Y-K Delta	July-Aug.	11
Dry tundra	61°	11	-	eddy corr.	-	Alaska, Y-K Delta	July-Aug.	12
Wet meadow tundra	"	29	-		-			
Lake (wind at 5 m/sec)	"	57	-		-			
(integrated areal mean)	"	25	-		-			
(integrated areal means)	61°	44	-	eddy corr.	25-85	Alaska, Y-K Delta	July-Aug.	13
Wet moss carpet	~70°S	1.6	-	208	0.03-20.3	Antarctica, Signy Isl.	Dec.-Mar.	14

BOREAL

HABITAT	LATITUTE	AVG. FLUX	ANNUAL FLUX (g/m2/yr)	N	RANGE	SITE	MEAS. PERIOD	REF
Forested bogs	47°	100	-	8	19-206	Minnesota, Marcell Forest & Zerkel	Aug.	15
Nonforested bogs	"	306	-	24	33-1943			
Forested fens	"	85	-	5	3-171			
Wild rice bed	"	493	-	4	127-883			
Sedge meadow	"	664	-	1	-			
Forested bogs	47°	89	-	55	11-694	Minnesota, Marcell Forest & Red Lake	May-Aug.	16
Nonforested bogs	"	199	-	77	18-866			
Forested fen	"	142	-	12	68-263			
Nonforested fens	"	348	-	35	152-711			
Nonforested bog	47°	177	-	eddy corr.	120-270	Minnesota, Marcell Forest	Aug.	17
Forested bog (hummock)	47°	21	3.5	36	2-48	Minnesota, Marcell Forest	Annual	18
Forested bog (hollow)	"	93	13.8	36	6-246			
Fen lagg	"	121	12.6	27	-1-482			
Nonforested bog	"	356	43.1	68	0-1056			
Nonforested fen	"	402	65.7	37	11-767			
Nonforested bog	54-55°	0	0	90	0	Alberta, Canada	May - Oct.	19
Nonforested poor fen	"	1	0.1	90	0-22			
Nonforested rich fen	"	65	9.5	90	0-1976			
Forested rich fen	"	24	3.4	90	0-1820			
Sedge meadow	"	148	21.7	90	0-1985			

HABITAT	LATITUTE	AVG. FLUX	ANNUAL FLUX (g/m2/yr)	N	RANGE	SITE	MEAS. PERIOD	REF
Beaver pond	"	518	76.2	90	0-12,068			
Nonforested fens	55°	30.5	-	80	0-112	Schef-ferville, Canada	June-Aug.	20
Nonforested fens: center	55°	72	-	205	29-125	Schef-ferville, Canada	June-Sept.	21
margin	"	30	-	195	9-65			
pools/ flooded	"	33	-	185	24-40			
Forest/fen margin	55°	28	-	255	0.6-51			
Patterned nonforested fens: ridges	"	7.5	-	110	5-9			
pools	"	48	-	85	32-66			
(calc. regional mean)+	"	18						
Horiz. rich fen	55°	-	3	-	-3-176	Schef-ferville, Canada	May-Sept. (multi-yr)	22
Horiz. poor fen	"	-	9.8	-	12-343			
Ribbed fen: ridge	"	-	1.3	-	1-25			
pools	"	-	4.5/9.9	-	1-260			
Basin swamps	45°	-	1.2/4.2	-	-3-207	Mont St. Hilaire Canada	May-Aug. (multi-yr)	
Domed bog: center	"	-	0.1	-	-11-10			
margin	"	-	0.1	-	-10-9			
Beaver ponds	45°	90.6 29.7 47.4	7.6 " "	56 65 65	0.9-246 0.3-300 0.2-369	low boreal forest, Canada	May-Oct.	23

HABITAT	LATITUTE	AVG. FLUX	ANNUAL FLUX (g/m2/yr)	N	RANGE	SITE	MEAS. PERIOD	REF
Conifer swamps	"	7.1 0.15 0.2 0.2	0.18 " " "	123 132 148 149	-0.2-236 0.1-10 -0.2-6 -0.2-9			
Mixed hardwood swamps	45°	1.2 0.25	0.1 "	141 139	-0.3-28 -5.8-10			
Thicket swamps	"	69.3 0.4	4.7 "	145 144	0-304 -0.3-37			
Marshes	"	1.2 0.5	0.1 "	72 134	-0.1-36 -0.3-26			
Open bog	"	20.6	1.7	65	-0.1-140			
Forested bog	"	5.8	"	68	-0.1-107			
Fen	"	3.0	0.4	62	-0.2-78.2			
Blanket bog: pool	55°	-	9.3	36	-	Moor House Nat.Res England	Annual	24
lawn	"	-	5.3	36	-			
hummock	"	-	1.3	36	-			
(integrated areal means)	55°	-	-	-	0-50	Hudson Bay Low-lands, Canada	July	25, 26
(integrated areal mean)	55°	16	-	-	-	Kino-sheo Lake, Canada	July	27
Ponds & lakes	55°	26	-	-	-	Kinosheo Lake, Canada	July	28
Fen ponds	56°	160	-	-	-	Coastal & int. Hudson Bay		
Open water	55°	12	1.5	-	0.2-146	South-ern Hudson Bay Low-lands Canada	June-Oct.	29
Marshes	"	31	2.3	-	-2.3-274			
Shrub & Treed Fen	"	2.5	0.4	-	-2.4-32			
Open Fen	"	7.9	0.7	-	-1.6-298			

HABITAT	LATITUTE	AVG. FLUX	ANNUAL FLUX (g/m2/yr)	N	RANGE	SITE	MEAS. PERIOD	REF .
Fen pools	"	133	13.8	-	21-544			
Bog pools	"	60	6.1	-	2.2-665			
Open bog	"	54	4.6	-	-1.7-1356			
Shrub-rich Bog	"	48	4.0	-	-1.5-1627			
Treed Bog	"	1.8	0.2	-	-1.7-66			
Conifer Forest	"	3.3	0.2	-	-2.2-50			

* Calculated from surface water concentrations, based on a wind speed of 5 m/sec.

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

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Appendix E: Methane Flux from Tussock Tundra (Warm Season Only)

(Fluxes made using enclosure techniques
unless otherwise noted; Flux units of $mgCH_4/m^2/d$)

MICROHABITAT	WATER LEVEL/INFO	AVG. FLUX	STD. DEV.	STD. ERROR	REF.
Ombrotrophic communities hummock	471[1]	1.1	0.71	0.32	1
interhummock	1288[1]	3	2.04	1.02	
shallow depression	1691[1]	16.5	7.8	3.5	
deeper depression	2540[1]	25.8	6.4	2.9	
Summer tussock tundra composite- (1987)	-	22.4	-	-	2
Tussocks (1987)	-	29.5	-	-	3
Tussocks (1988)	-10-9[2]	60.8	-	-	
Tussocks (1989)	-29-9[2]	48.8	-	-	
Tussocks (1990)	-12-11[2]	96.8	-	-	
Intertussocks (1987)	-	2.8	-	-	
Intertussocks (1988)	-6-15[2]	25.2	-	-	
Intertussocks (1989)	-29-10[2]	12.4	-	-	
Intertussocks (1990)	0-20[2]	5.9	-	-	
Moss (1987)	-	0.9	-	-	
Moss (1988)	-18-0[2]	10.1	-	-	
Moss (1989)	-40-4[2]	29	-	-	
Moss (1990)	-21-15[2]	3.8	-	-	
Meadow/moist tundra MP 298	+2 cm	32.6	-	-	4
MP 346	+2-5 cm	77.6	-	14.1	
MP 416	+3 cm	152	-	8.5	
MP 416	H_2O sat.	53.7	-	5.4	
MP 298	-30 cm	3.1	-	3.1	
MP 318	-15 cm	0.3	-	0.3	
MP 346	-13 cm	12.5	-	-	

MICROHABITAT	WATER LEVEL/INFO	AVG. FLUX	STD. DEV.	STD. ERROR	REF.
Moist tundra	-	31	19-52[3]	-	5
Tussocks	-	3.4	-	3.1	6
Intertussocks	-	2.9	-	2.4	
Upland tundra (low tussocks)	dry	2.3	-	1.1	7
Upland tundra (low tussocks)	dry	11	-	3	8

[1] Avg. % water dry wgt.

[2] Seasonal range in water table, all three habitat sub-sites.

[3] 95% confidence interval.

REFERENCES:

1: Svensson and Rosswall, 1984
2: Whalen and Reeburgh, 1988
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6: Morrissey and Livingston, in press
7: Bartlett et al. 1992
8: Fan et al. 1992

Appendix F: Mean Regional Methane Fluxes (High Latitudes)

REGION	SITE	TECHNIQUE	AVG. FLUX ($mgCH_4/m^2/d$)	RANGE ($mgCH_4/m^2/d$)
Arctic	Y-K[1] Delta-entire area	enclosures	48.5	-
	Y-K Delta-flight paths	aircraft eddy correlation	44	25 - 85
	Y-K Delta-tower area	enclosures	27	-
	Y-K Delta-tower area	tower eddy correlation	25	-
	Y-K Delta-tower area (1)[2]	aircraft eddy correlation	-	40 - 60
	tower area (2a)	"	59.7	-
	tower area (2b)	"	72.1	-
	North Slope	enclosures	17.3	-
Boreal	Schefferville area	enclosures	18	-
	Schefferville tower area	tower eddy correlation	16	-
	Schefferville tower area (July 17)	tower eddy correlation	-	19 - 24
	(July 25)		-	10 - 29
	Schefferville tower area (July 17 & 25)	aircraft eddy correlation	-	24 - 29
	Schefferville flight paths	aircraft eddy correlation	-	0 - 50

[1]Yukon-Kuskokwim Delta
[2]Numbers in parentheses indicate different flights and legs of flights.

Data from:

Bartlett et al. 1992
Fan et al. 1992
Ritter et al. 1992
Livingston and Morrissey, in press
Moore, Roulet, and Knowles, 1990
Edwards et al., 1991
Ritter et al., 1991
Schiff et al., 1991
Roulet, pers. com.

Appendix G: Rates of CH_4 Uptake in Natural Ecosystems

(Fluxes made using enclosure techniques unless otherwise noted; Flux units of $mgCH_4/m^2/d$)

-- ARCTIC/SUBARCTIC WETLANDS --

HABITAT	LATITUDE	AVG/MEDIAN RATE	RANGE	REFERENCE
Moist tundra meadow	53°	-2.7	-	1
Coastal tundra	~69°	-0.86	-0.5 - -1.2	2
Upland tundra	61°	-0.78	-0.2 - -2.1	3
Alpine tundra	~68°	-0.2	-	4

-- ARCTIC/SUBARCTIC FORESTS --

HABITAT	LATITUDE	AVG/MEDIAN RATE	RANGE	REFERENCE
Spruce forest	~68°	-0.3	-	4
Floodplain taiga	65°	-	0 - -1.0	5
Upland taiga	"	-	0 - -1.8	

-- BOREAL WETLANDS --

HABITAT	LATITUDE	AVG/MEDIAN RATE	RANGE	REFERENCE
Bog lagg	47°	-	-1.0	6
Rich fen	55°	-	0 - -5	7
Forested swamp	45°	-	0 - -3	
Forested swamp	"	-	0 - -8	
Domed bog	"	-	0 - -10	
Fen	45°	-	0 - -0.2	8
Bogs	"	-	0 - -0.1	
Conifer swamps	"	-	0 - -0.2	
Mixed hardwood swamps	"	-	0 - -5.8	
Thicket swamps	45°	-	0 - -0.3	
Marsh	"	-	0 - -0.3	
Forests	55°	0.53	-	9
	"	0.27	-	
	"	1.57	-	

-- **TEMPERATE WETLANDS** --

HABITAT	LATITUDE	AVG/MEDIAN RATE	RANGE	REFERENCE
Ombrotrophic bog	39°	-	0 - -6.7	10
Minerotrophic fen	"	-	0 - -7.7	
Forested swamp	37°	-	-0.5 - -6	11
Salt marsh	37°	-1.4	-0.7 - -2.7	12
Salt marsh	39°	-1.2	-1 - -1.4	
Salt marsh	38°	-1.8	-1.6 - -2	
Salt marsh	33°	-3.2	-2.1 - -3.9	
Salt marsh	30°	-3.2	-	

-- **TEMPERATE FORESTS** --

HABITAT	LATITUDE	AVG/MEDIAN RATE	RANGE	REFERENCE
Mixed forests	39°	-	0 - -6.5	10
Red pine	"	-	0 - -6.5	
Red spruce	"	-	0 - -1.2	
Hardwood forest	43°	-0.28	-	13
Mixed forest	43°	-1.6	0 - -4.9	14
Mixed hardwood/ Conifer forest	44°	-	-0.9 - -3.2	15
Deciduous forest	42°	-4.2	-3.5 - -5.1	16
Evergreen forest	"	-3.5	-3.2 - -4.2	
Beech/spruce forest	49°	-3.48[1]	-2.5 - -5.8	17
Beech/spruce forest	"	-3.45[1]	-1.9 - -5.8	
Beech/oak/ maple forest	"	-0.82[1]	-0.5 - -2.2	
Spruce forest	"	-0.25[1]	-0.1 - -0.5	
Mixed forest	"	-1.01[1]	-0.5 - -1.6	

-- **TEMPERATE GRASSLANDS** --

HABITAT	LATITUDE	AVG/MEDIAN RATE	RANGE	REFERENCE
Shortgrass steppe	41°	-0.61	-0.35 - -0.84	18

-- **TEMPERATE DESERT** --

HABITAT	LATITUDE	AVG/MEDIAN RATE	RANGE	REFERENCE
Sand w/sparse vegetation	37°	-0.066	0 - -4.38	19

-- **TROPICAL/SUBTROPICAL WETLANDS** --

HABITAT	LATITUDE	AVG/MEDIAN RATE	RANGE	REFERENCE
Open water	3°	-	-10.5	20
Non-forest swamp	"	-	-11.3	21

-- **TROPICAL/SUBTROPICAL FORESTS** --

HABITAT	LATITUDE	AVG/MEDIAN RATE	RANGE	REFERENCE
Dry flooded forest	2°	-1.9	-0.8 - -4.6	22
Upland moist forest	3°	-0.38	-	13
Upland forest	3°	-0.71	-	23
Secondary forest	1°	-0.8	-	
Tabunoco forest	18°	-0.58	-	
Semi-deciduous forest-oxisol soils	9°	-0.78	-	24
Semi-deciduous forest-alfisol soils	9°	-0.35	-	
Semi-deciduous forest	8°	-1.15	-	25
Dry evergreen forest:	4°			26
Hillside	"	-1.7	-0.6 - -2.5	
Valley	"	-0.3	0 - -1.1	
Virgin forest - clay soils	3°	-0.78	-0.36 - -1.32	27
Virgin forest - sandy soils	"	-1.71	-1.57 - -1.85	

-- **TROPICAL/SUBTROPICAL GRASSLANDS** --

HABITAT	LATITUDE	AVG/MEDIAN RATE	RANGE	REFERENCE
Dry savanna	0°	-0.61	-0.46 - -0.81	28
Dry sandy savanna	5°	-0.07	-	
Savanna - near termite mounds	39°	-0.96	-0.25 - -2.33	29
Broad-leaf savanna-near termite mounds	25°	-1.25	-0.31 - -2.45	30

[1] Calculated from soil gas profiles and radon exchange rates.

REFERENCES:

1) Whalen and Reeburgh, 1990a
2) King et al., 1989
3) Bartlett et al. 1992
4) Whalen and Reeburgh, 1990b
5) Whalen et al., 1991
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7) Moore and Knowles, 1990
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9) King et al., 1991
10) Yavitt et al., 1990
11) Harriss et al., 1982
12) Bartlett et al., 1985
13) Keller et al., 1983
14) Crill, 1991
15) King and Adamsen, in press
16) Steudler et al., 1990
17) Born et al., 1990
18) Mosier et al., 1991
19) Striegl et al., 1992
20) Bartlett et al., 1988
21) Bartlett et al., 1990
22) Tathy et al., 1992
23) Keller et al., 1986
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25) Scharffe et al., 1990
26) Delmas et al, 1992a
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