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MARTIN MARIETTA

Report of a Workshop on Climate Feedbacks and the Role of Peatlands, Tundra, and Boreal Ecosystems in the Global Carbon Cycle

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Wilfred M. Post

ENVIRONMENTAL SCIENCES DIVISION
PUBLICATION NO. 3289



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Environmental Sciences Division

**Report of a Workshop on Climate Feedbacks
and the Role of Peatlands, Tundra, and
Boreal Ecosystems in the Global Carbon Cycle**

Wilfred M. Post, Editor

Environmental Sciences Division
Publication No. 3289

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I thank all of the participants who attended the workshop for their hard work and generous contributions to the accomplishments made there. Their willingness to share ideas and to forge consensus so that computations could be made was commendable. The material in this report is a compilation of drafts of material written at the workshop or shortly after the workshop. The computations summarized in Section 2 represent the work of all the participants, with the arctic and boreal subsections rendered into logical progressions of ideas by G. Shaver and J. Pastor, respectively. The following individuals contributed the materials for Section 3: P. Glaser, 3.1; D. Grigal and A. Khalil, 3.2; A. Khalil, 3.3; P. Glaser, 3.4; and K. Weider, 3.5.

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ABSTRACT

A workshop held in Oak Ridge, Tennessee, on April 4-6, 1988, assembled leading North American researchers to discuss recent research results and accomplish three goals: (1) estimate, given current knowledge, the net flux of carbon cycle gases between northern ecosystems and the atmosphere under projected climates for atmospheric CO₂ concentrations approaching 580 ppmv; (2) Determine the key uncertainties in such a calculation and the short-term research necessary to significantly reduce these uncertainties; and (3) Identify long-term research objectives that will increase our confidence in the accuracy of carbon cycle gas flux estimates in northern ecosystems.

The first day of technical presentations outlined the latest research findings from field and modeling studies of these peat-rich ecosystems. The research summaries included studies to (1) understand the relationships between climate, direct effects of increased CO₂, nutrient cycling and organic matter production and accumulation in peatland, tundra, and boreal ecosystems; and (2) extend current experimental methods of using remote sensing for the difficult task of extrapolating stand or sub-system processes over regional or global scales. A discussion of these presentations is not included in this workshop report. The information contained in these presentations has or will appear in publications by various participants, who should be contacted directly for additional information.

On the second day, working groups were formed to identify the known information and define a strategy to assemble this information into an estimate of future global fluxes of carbon dioxide and methane. These working groups concentrated on various processes operating in these diverse ecosystems and their response to climate change. A separate working group discussed regional/global data and methodologies for scaling the locally derived process information to global estimates.

The working groups concluded that processes in tundra, boreal peatland, and boreal upland ecosystems have different sensitivities to climate. As a result, two working groups, tundra and boreal, were formed on the third day to provide draft calculations for an upper bound on the increased net biosphere-atmosphere fluxes of carbon dioxide and methane under a climate with twice the ambient CO₂. These estimates appear in the table below. For the purposes of calculation, an average annual temperature increase of 5° C was assumed (a conservative estimate for these latitudes). The important influence of hydrological factors on the anaerobic

conditions favorable for peat formation, and uncertainty in projected precipitation changes necessitated parallel computation for two climate regimes — warmer climate with unchanged hydrology (warm/wet) and warmer climate with water tables lowered by 10 cm (warm/dry). Finally, changes in climate will alter natural fire regimes that play a large role in peat storage in upland boreal ecosystems. The potential contribution of increased fire frequency in these ecosystems is computed as an additional CO₂ release. The effect of fires on methane production could also be as large, but too much uncertainty exists to include an estimate.

**Estimates of increased net flux rate of carbon cycle gases from
tundra and boreal ecosystems to the atmosphere**

Ecosystem	Net Flux (Pg C·year ⁻¹)			
	Warm/wet		Warm/dry	
	CO ₂	CH ₄	CO ₂	CH ₄
Tundra	1.3	0.1	1.6	0.1
Boreal (Peatland + Upland)	0.03	0.12	0.83	0.12
Increased fire (Boreal Upland)	0.4	+	0.8	+
Total without fire	1.33	0.22	2.43	0.22
Total with fire	1.73	0.22+	3.23	0.22+

The estimates of potential increased rates of CO₂ and CH₄ evolution from northern ecosystems are quite large. Some support is lent to these calculations by the observation that the predicted rise in global methane release is similar to the observed methane rise with comparable changes in climatic regimes at the end of the last glacial period (Aslam Khalil, Oregon Graduate Center, personal communication, 1988). We did not make a calculation of gas flux changes resulting from a warmer/wetter climate. There was an educated guess that the warm/wet climate calculations would not be altered except for increased rates of organic matter storage in land areas that would change from relatively dry to moister status. Participants were unprepared to make calculations of the change in land areas occupied by different ecosystem types. The accumulation rates in the newly moist areas would be slow

compared to decomposition rates in present-day peat-rich regions, so a warm/wet case climate would most likely result in somewhat lower, but not substantially lower changes than the warm/wet case.

This workshop report outlines the methods and assumptions that produced these calculations and discusses the uncertainties involved. This report also outlines research tasks, both short-term and long-term, that will be needed to reduce these uncertainties.

1. CO₂-INDUCED CLIMATE CHANGE IN NORTHERN LATITUDES

Past, current, and future increases of carbon cycle gases in the atmosphere will warm the global climate by a few degrees Celsius in the next century. Some warming is inevitable because of past emissions. Computer models project that the greatest climate changes will occur at high latitudes. The possible climate changes accompanying a doubling of the preindustrial atmospheric levels are large enough that carbon cycle dynamics of the carbon-rich ecosystems at high latitudes will be altered.

The stores of carbon, particularly in the soils and peats, of the boreal and tundra ecosystems of the world are large. Soils are estimated to contain 350 Pg C (Post et al. 1985), and estimates of peat stored in bogs range from 180 Pg C to 280 Pg C (Gorham 1988). These ecosystems are thought to be a small net sink of atmospheric carbon, on the order of 0.1–0.3 Pg C·year⁻¹ for atmospheric CO₂ since the last glacial retreat, reflecting the imbalance of production exceeding decomposition (Miller 1981, Gorham 1988). If climate change were to reverse this relationship, then large amounts of carbon would be subject to loss to the atmosphere. Whether or not this will occur and the rate at which shifts would occur depend on the magnitude and timing of climate change and the response of ecosystem carbon dynamics to these changes.

1.1 TEMPERATURE INCREASES

Some evidence indicates that a variable but widespread warming of 2 to 4°C has occurred at the permafrost surface during the 20th century (Lachenbruch and Marshall 1986). This represents possible direct evidence that may confirm the predictions of computer model results of climate response to increased atmospheric CO₂ levels. Computer models are the only predictive methods now available for quantitatively estimating the climatic changes expected to result from changes in the atmospheric composition of greenhouse gases. However, because of the complexity in modeling climate, the incorporation of different model assumptions, features, resolutions, inputs, parameters, and mechanisms results in different projections. We will not attempt to evaluate different models here. Rather, we present some results from the leading general circulation models (GCMs) to develop a general picture of the possible ranges of future climate in northern latitude regions.

2 *Climate Change*

Figures 1 and 2 show the projected changes in surface air temperature for different GCMs. They all predict large increases in temperatures between 45° and 80° latitude. The greatest changes are in winter temperatures, with most models predicting at least 8 to 10°C changes above 60° latitude with a doubling of CO₂. Changes in summer temperatures are less extreme with most models indicating a 2 to 4°C warming. The actual changes in a particular region may be greater or less than these zonal averages depending on a multitude of processes related to both local and global factors. The projections from these climate models for different regions are very uncertain (Grotch 1988), and it is premature to base region-specific calculations of ecosystem carbon cycle response for any particular region on the predictions of one or more projections from climate models.

1.2 PRECIPITATION AND SOIL MOISTURE CHANGES

The zonally averaged changes in precipitation are broadly similar in all the computer model studies. There is a marked increase in precipitation in high latitudes (Figure 3). The warming that accompanies the higher CO₂ concentrations increases the capacity of the atmosphere to hold moisture. An increase in the transport of warm moist air into high latitudes will result in greater precipitation (Schlesinger and Mitchell 1985).

Because these increases are zonal averages, some boreal and tundra regions will receive larger amounts and other regions will receive smaller amounts of precipitation. In addition, what is important is not the amount of precipitation, but the supply of available moisture that results from the balance between precipitation and evapotranspiration. The large projected temperature increases will increase evaporation; the supply of moisture to the surface or soil may not follow the same pattern as precipitation. The evaporation increases relatively uniformly with latitude. There are large increases in precipitation in tundra zones at high latitudes but small increases or even reductions near 40° to 50°, the southern portion of the boreal zone. In high latitudes the increase in precipitation generally exceeds evaporation, and there is an increase in soil moisture and runoff. The region near 40° to 50° will experience decreases in soil moisture and runoff (Schlesinger and Mitchell 1985).

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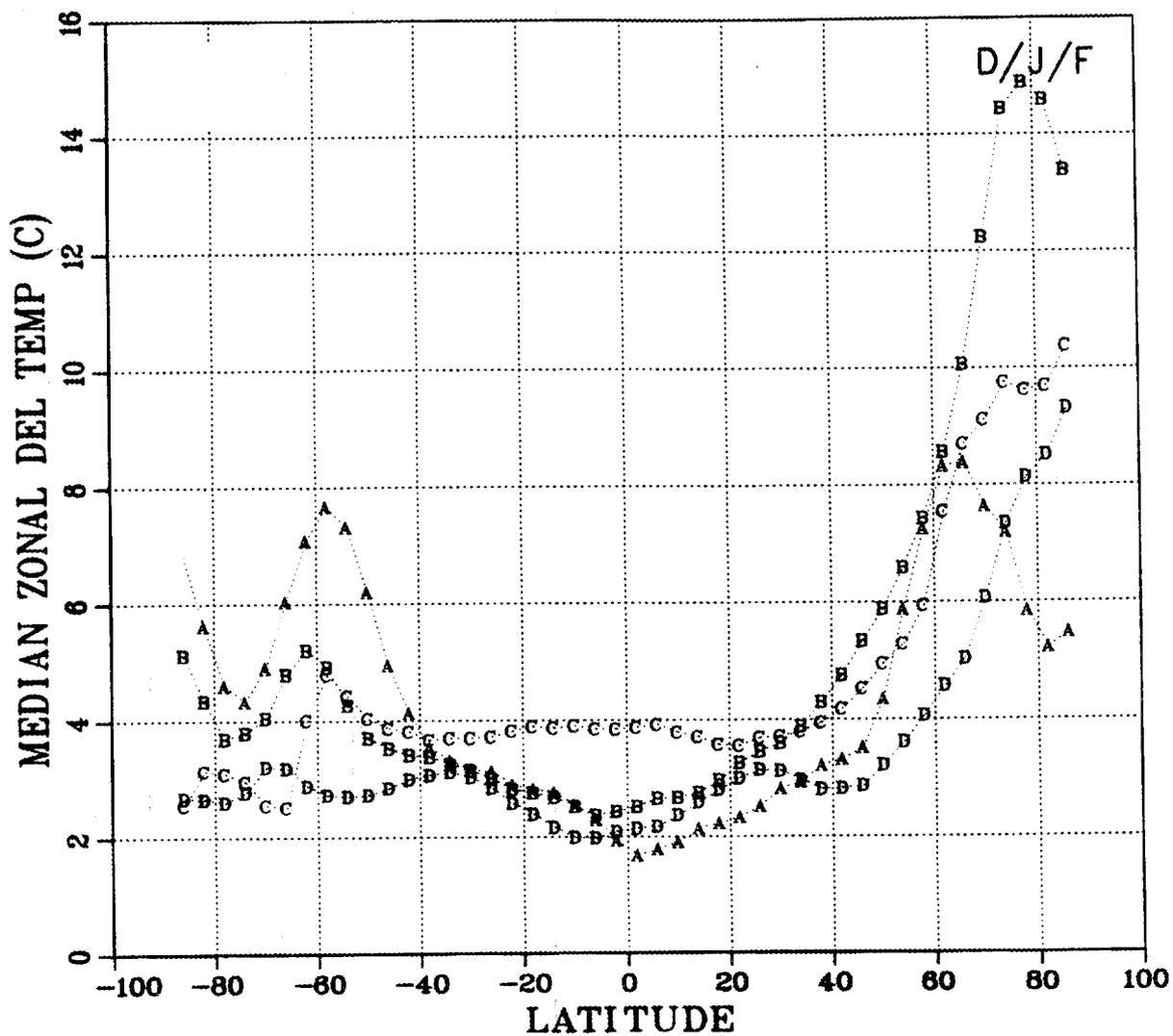


Fig. 1. Superimposed medians for four GCMs of the zonal distributions for the predicted change in surface air temperature due to a doubling of CO₂ for December/January/February. A = Community Climate Model (CCM), B = Geophysical Fluid Dynamics Laboratory model (GFDL), C = Goddard Institute of Space Science model (GISS), D = Oregon State University model (OSU) (from Grotch 1988, p. 136).

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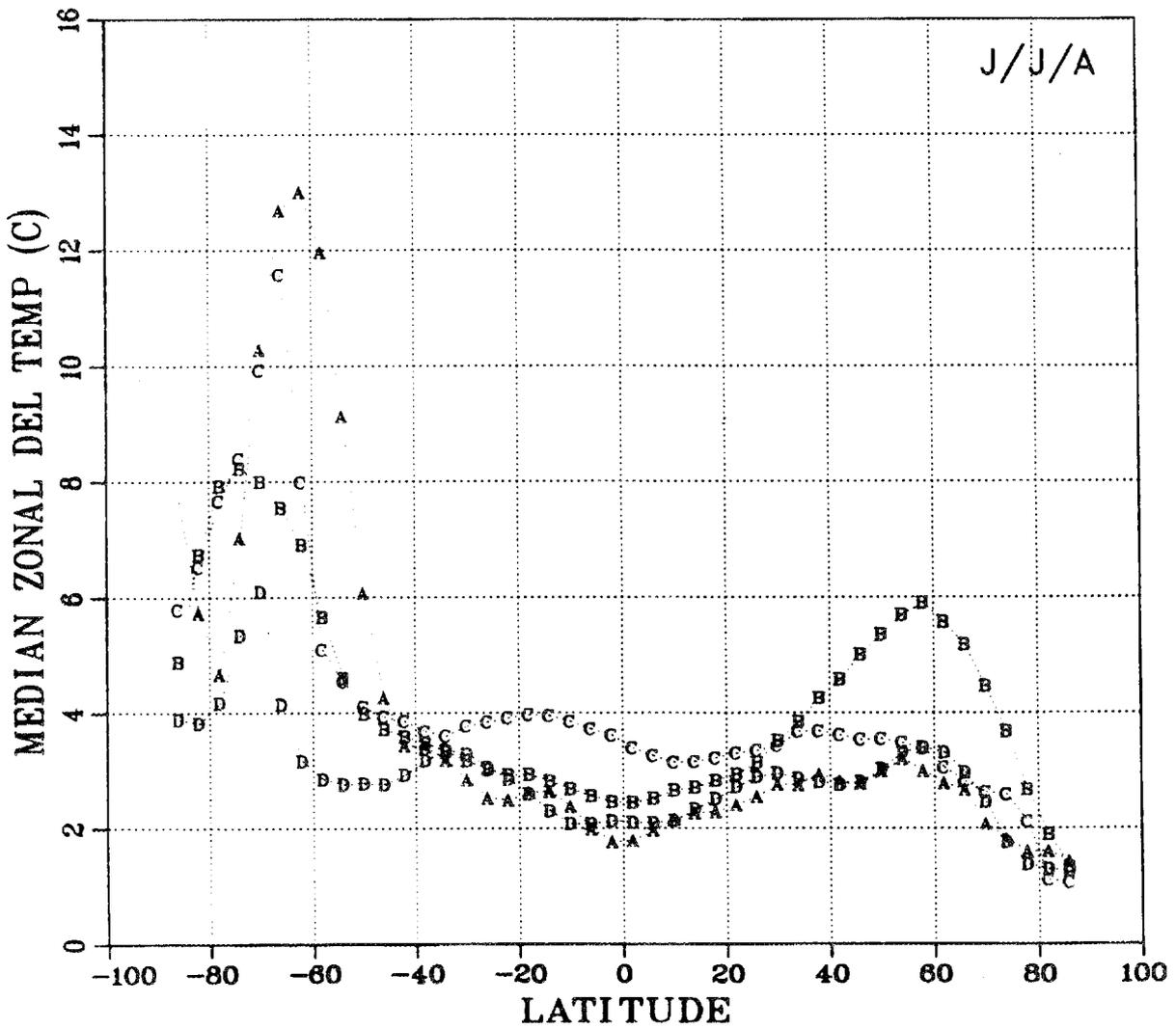


Fig. 2. Superimposed medians for four GCMs of the zonal distributions for the predicted change in surface air temperature due to a doubling of CO₂ for June/July/August. A = CCM, B = GFDL, C = GISS, D = OSU (from Grotch 1988, p. 137).

ORNL-DWG 89-8339

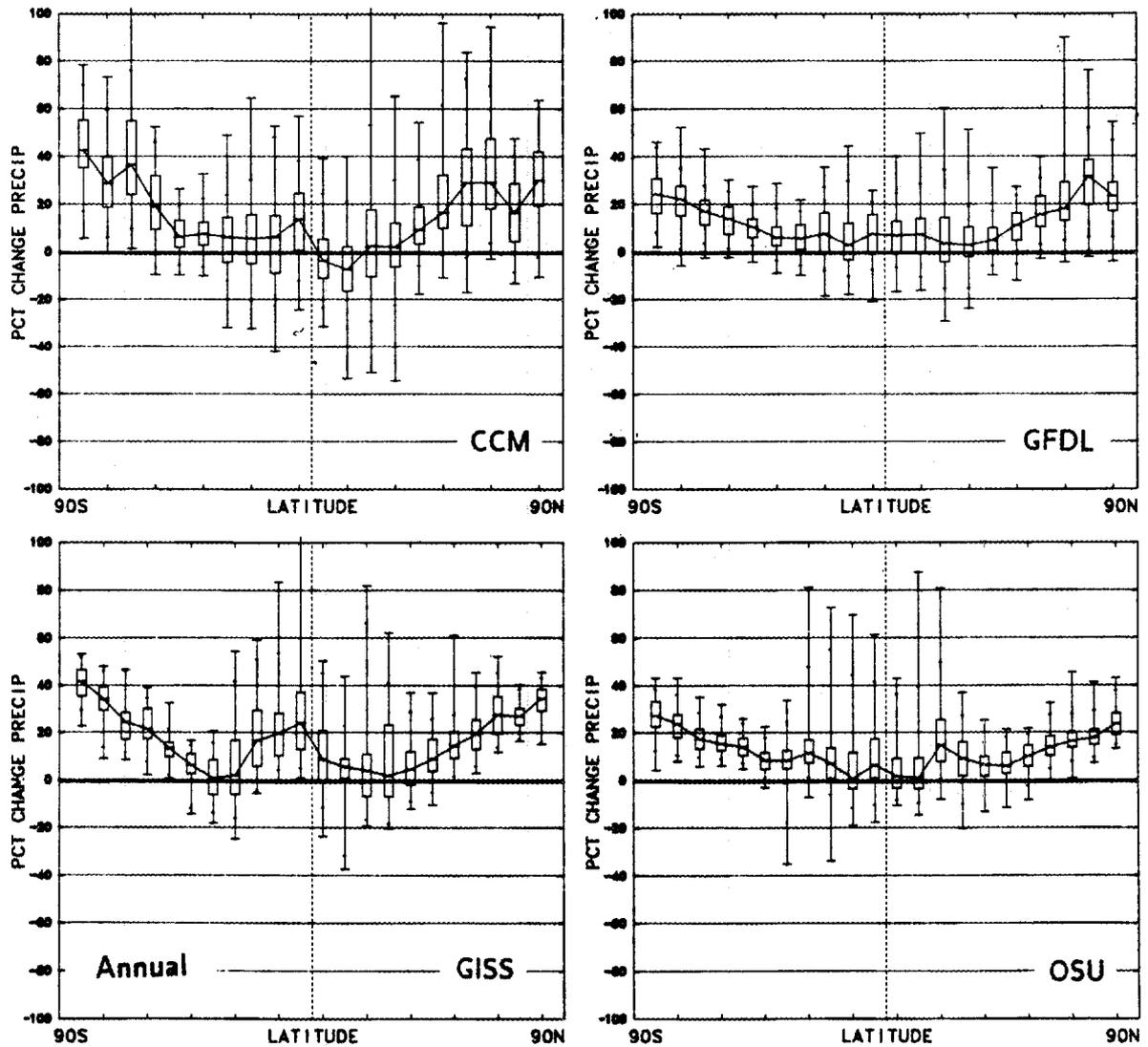


Fig. 3. Zonal distribution of the percent change in annual precipitation for the four models. The zonal medians are connected with a heavy central line (from Grotch 1988, p. 226).

1.3 SELECTION OF EXTREME CLIMATE REGIMES

The current status of climate modeling is that GCMs simulate the present and future climate imperfectly. Part of the problem is that GCMs do not resolve all of the physical processes that may be important to climate and climate change, and estimates range over 14 orders of magnitude. Current models permit the resolution of physical processes over only two orders of magnitude. The smaller scale processes important in cloud formation are not simulated. Most models simulate some climatic quantities reasonably well, such as surface air temperature. The results of climate GCMs often agree well with each other over large scales (global/zonal), but when the model results are examined over smaller scales, different models make widely different predictions (Grotch 1988). None of the models can be used for detailed regional or seasonal perturbation studies.

To make predictions of the response of northern ecosystems in the global carbon cycle to a CO₂-altered climate, we decided to choose likely but extreme climate conditions that would allow the construction of reasonable upper bounds over the most likely response. The calculations presented in the next sections are done for two contrasting climate regimes – warmer and wetter climate (warm/wet), and warmer and drier climate (warm/dry). Both climate regimes assume a 5°C temperature increase. This is a reasonable figure for boreal zones but is probably an underestimate for tundra zones. Since the regions under consideration already have greater inputs into soil moisture than losses, the wetter climate regime is assumed to result in no changes in current soil moisture patterns. Thus a carbon sink associated with expansion of wetlands and moist ecosystem types into currently drier ecosystem regions is not considered although such expansion may occur. The drier climate regime is assumed to result in a 10-cm drop in available soil moisture through decreases in precipitation and increases in evapotranspiration.

2. PROJECTED CHANGES IN CARBON CYCLE GAS FLUX UNDER CO₂-ALTERED CLIMATE

2.1 ARCTIC ECOSYSTEMS

In this section estimates are made of the net changes in CO₂ releases from arctic ecosystems that might result from a global warming. The two scenarios considered are (1) warm and wet and (2) warm and dry. Also attempted are very preliminary predictions of the net changes in methane releases under the same two scenarios.

2.1.1 Data sources and assumptions

We used, as a starting point, vegetation classes, production and biomass estimates, and areal coverage estimates in Table 3 (page 9) of the 1980 San Diego workshop report (Miller 1981). For total soil respiration we used recent, unpublished data of Nadelhoffer, Shaver, and Giblin (Gaius Shaver, Marine Biological Laboratory, personal communication, 1988), collected from ecosystem types similar to those defined in the San Diego report. We assumed that half of total soil respiration was attributable to roots and half to soil organic matter. Because they contain so little carbon or cover only a small area, polar deserts and tall shrub communities were excluded from our calculations.

For our first estimate of CO₂ release, we assumed that the principal climatic changes would be a 5°C increase in air and soil temperatures during the growing season, combined with an increase in the length of the unfrozen period of about 33%, or 30 days. The temperature change alone was assumed to double the soil respiration rate; doing so for a 33% longer period resulted in a total annual increase by a factor of 2.6. We did not include any assumptions about changes in the depth of the permafrost or the water table, and we assumed that the potential for increased plant growth due to increased nutrient releases was negligible, at least in the short term (Gaius Shaver, Marine Biological Laboratory, personal communication, 1988).

Our second estimate of CO₂ release was based primarily on an assumption that permafrost melting and increased drainage, regardless of precipitation changes, would lower the water table, thus stimulating peat oxidation according to the Clymo model (Clymo 1984). We used a peat oxidation rate constant of 0.1 per year above the water table and assumed a reduction of 10 cm in the water table/permafrost level. This would cause a loss of about 1 cm of peat depth in the first year. We assumed that the carbon content of 1 mm of peat is 65 g C·m⁻² or 650 g C·cm⁻¹·m⁻²,

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and multiplied this amount by the areas of wet and moist tundras (approximately 2×10^6 km²).

2.1.2 Results

Method 1 — We estimate that an increase of 5°C with a 33% longer growing season would result in an increased carbon loss from arctic ecosystems of about 0.2 Pg C per year as CO₂ (Table 1).

Method 2 — A reduction in the water table of 10 cm, due either to greater depth of thaw or increased drainage, or both, should result in a loss of carbon from soils of wet and moist tundras of about 1.3 Pg C per year as CO₂ or CH₄.

Methane releases — Roughly, we estimated that the increase in methane release would be 10 to 20 percent of the increase in CO₂ release due to increased drainage, or 0.13–0.26 Pg CH₄-C per year. The larger amount is about equal to the total annual anthropogenically caused methane release for the world.

Warm/wet versus warm/dry scenarios — We were uncertain about the effect of wet versus dry conditions on net carbon release because the melting of permafrost should be increased by both (1) greater heat conduction into the soil under wet conditions and (2) greater insolation and higher surface temperatures under dry conditions. However, we have assumed a 25% greater respiration rate under the dry scenario because the greatest temperature increases will be in the upper aerobic zone.

2.1.3 Summary

Because carbon releases estimated under method 2 include essentially all of the releases estimated in method 1, we decided to use only method 2. Thus, under warm/wet conditions we predict a total release of 1.3 Pg C per year from arctic ecosystems, of which at least 0.1 Pg C will be methane. Under warm/dry conditions we predict a loss of 1.6 Pg C, with again about 0.1 Pg C as methane.

Overall, this estimate is conservative because it does not include carbon losses from drier tundras with smaller but still significant accumulations of soil organic matter. The estimate also does not include possibly much greater releases due to massive thermokarst erosion (melting of ice-rich permafrost), or to the flooding of extensive areas by large, heterotrophic lakes. Finally, one very large additional source of both CO₂ and methane is the large amount of these gases already locked in permafrost, which should readily escape if the permafrost melts. We cannot

currently predict, even roughly, the amount of permafrost melting that may occur and do not have estimates of the concentrations of gases in permafrost.

We considered the potential stimulation of carbon accumulation in plants that would result from the release of nutrients tied up in soil organic matter, but decided it would probably be insignificant relative to soil carbon losses, at least until most of the soil carbon is lost. Preliminary studies indicate that the ratio of carbon respired to nitrogen or phosphorus mineralized in tundra soils is 10-50 times the C/N or C/P ratios of tundra plant biomass. In the longer term, however, there is a strong potential for net carbon storage because the C/N and C/P ratios of bulk soil are much lower than the corresponding ratios in biomass. More research is needed on the fate of other elements in soil organic matter — are they lost from the system or taken up by plants? Will climate change in the Arctic be associated with new inputs or losses of these other elements, which are now strongly limiting to plant biomass and carbon accumulation?

2.2 BOREAL ECOSYSTEMS

The boreal zone can be considered to consist of two different ecosystem types, bogs and upland forests, that have large stores of undecomposed organic matter. Bogs accumulate peat at a slow but persistent rate due to water-saturated layers, resulting in low ecosystem production and nearly total inhibition of decomposition. Boreal upland forests also accumulate thick surface organic layers. The ecosystem production rate of organic matter is higher than in bogs, and the decomposition rate is higher but still low enough for net accumulation to occur due to low nutrient status, cold soil temperatures, conditions of partial water saturation, and/or permafrost.

As in the arctic estimates of net change in CO₂ release, we used two scenarios to make estimates — warm/wet, and warm/dry. Also included are estimates of increased releases due to changes in forest fire frequency in boreal uplands, expected to increase under new climate conditions.

2.2.1 Bogs

Peat bogs consist of two layers: an upper, typically thin, aerobic layer and an underlying water-saturated, anaerobic layer. Net CH₄ evolution is the result of production in the anaerobic layer, minus possible oxidation in the upper aerobic layer. CO₂ is produced in both layers.

Table 1. Estimate of effects of 5°C increase in the arctic growing season temperature, plus increase of 33% in growing season length, on C losses due to soil respiration

Ecosystem	Total area (10 ⁶ km ²)	Active soil carbon (Pg C)	Current soil respiration (g C·m ⁻² ·yr ⁻¹)	CH ₄ release (g C·m ⁻² ·yr ⁻¹)	New soil respiration (g C·m ⁻² ·yr ⁻¹)	Additional carbon loss (Pg C·yr ⁻¹)
Wet sedge tundra	1.0	13.4	15.0	Same?	39.0	0.024
Tussock tundra	0.9	26.1	32.0	Less	83.2	0.046
Low shrub tundra	1.3	4.9	45.0	Less	117.0	0.094
Polar semidesert	1.5	10.8	125.0	Much less	32.5	0.030
Total						0.19

2.2.1.1 Anaerobic zone of peat bogs

The following assumptions were used to calculate the increased rate of carbon cycle gases from the saturated zone of bogs:

1. current microbial respiration rate is $200 \text{ mg C}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ as CH_4 (annual average) or $73 \text{ g C}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$;
2. with every 1°C rise in temperature, there will be a 10% increase in the current rate of respiration; and
3. total area of boreal bogs is $3.2 \times 10^{12} \text{ m}^2$.

Multiplying the numbers above gives an annual increase of 0.023 Pg C in the atmosphere per each degree rise in temperature, or approximately 0.12 Pg C per 5°C rise. This is actually a conservative estimate, as the increase in respiration is assumed to be linear with every degree rise. In fact, the increase will probably follow a logarithmic (Q_{10}) rule. This increase would occur with climatic warming with or without any change in precipitation.

2.2.1.2 Aerobic zone of peat bogs

A warmer and dryer climate would cause a drop in the water table, and so additional estimates need to be made for aerobic respiration from any increase in thickness of the aerobic surface layer. For this estimate, we assume

1. bulk density of aerobic layer is $0.05 \text{ g}\cdot\text{cm}^{-3}$;
2. carbon content of aerobic layer is $0.5 \text{ g C}\cdot\text{g}^{-1}$; and
3. total area is $3.2 \times 10^{12} \text{ m}^2$.

Multiplying these numbers gives a value of 0.8 Pg C newly available for aerobic respiration per centimeter drop in the water table. Assuming a 5-cm drop with climatic warming over 5 years, the average annual increase from the aerobic layer is 0.8 Pg $\text{CO}_2\text{-C}$. This is probably a liberal estimate because the drop in water tables may occur much more slowly.

2.2.2 Upland forests

2.2.2.1 Forest floor organic matter

Increases in soil temperatures due to climate warming will result in increased decomposition of the organic mat on the floor of boreal upland forests. Assuming that

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1. average thickness is 25 cm,
2. area of upland boreal forest is 10^{11} m²,
3. bulk density is 0.2 g·cm⁻³,
4. carbon content is 0.5 g C·g⁻¹ soil,
5. current annual respiration rate is 2.0%, and
6. current respiration rate will increase 10% with every 1°C rise in temperature,

we can multiply these and estimate an annual increase of 0.005 Pg C release per degree rise, or 0.025 Pg C per 5°C rise in temperature. This is probably a conservative estimate for the same reasons as given for increases in the saturated zone of histosols. However, it may be balanced by a projected increase in forest productivity due to enhanced nutrient availability, temperature increases, and northern hardwoods migration, especially if drought stress does not increase.

2.2.2.2 Losses due to fire

The increases discussed earlier are projected to occur from soils with climatic warming regardless of any change in precipitation. Terrestrial ecosystems may, however, experience dry periods more frequently because of increased temperatures and decreased precipitation. The resultant increases in fire frequency would yield additional carbon dioxide releases to the atmosphere from live biomass and detritus. If we assume that

1. current carbon yield from boreal fires is 1 Pg C·year⁻¹, mainly from small noncatastrophic fires that burn ground cover (Olson 1981), and
2. a warmer climate will produce a 50% increase in these non-catastrophic fires,

a total increase of 0.5 Pg C·year⁻¹ from small noncatastrophic fires can be estimated. To this must be added carbon released as a result of increased frequency of catastrophic fires. To calculate this, we assume the following:

3. 30–40 Pg C is in live biomass,
4. 0.2 Pg C is in detritus, and

5. the increase in catastrophic fire frequency will be such that 10% of the forest will burn in 10% of the years.

This correction yields an additional $0.3 \text{ Pg C}\cdot\text{year}^{-1}$ from catastrophic fires, for a total of $0.8 \text{ Pg C}\cdot\text{year}^{-1}$ from increased fire frequency of both types. This estimate assumes a warm/dry climate. For a warm/wet climate, the increase in fire frequency will likely be only half this amount, or $0.4 \text{ Pg C}\cdot\text{year}^{-1}$.

2.2.3 Summary

Preliminary calculations indicate that the greatest sources of carbon from boreal upland forests with climate warming will most likely result from increased decomposition of the upper layer of peat from bogs, and from increased fire frequency in upland forests. A warmer and drier climate would yield an additional annual maximum of $0.8 \text{ Pg CO}_2\text{-C}$ to the atmosphere from the unsaturated zone of bogs, probably in an early pulse. Increases in upland boreal forest fires may be just as large. However, increased methane generation from the saturated zones of peat bogs and other Histosols may have an even larger impact in terms of feedback to further climate warming. A warmer climate would increase anaerobic respiration in the saturated zone of bogs, yielding an annual increase of 0.12 Pg C as methane to the atmosphere. Methane is 10 times more effective in increasing atmospheric temperature than CO_2 , so the $0.12 \text{ Pg CH}_4\text{-C}$ increased flux from this source would be equivalent to $1.2 \text{ Pg CO}_2\text{-C}$ in terms of the greenhouse effect. Increased soil respiration in upland forest would contribute only a minor amount of CO_2 , which may be offset by increases in forest production where soil moisture is not limiting.

2.3 TOTAL ARCTIC AND BOREAL RESPONSE

Combining the calculations for the tundra and boreal zones, we arrive at an estimate of 1.6 to $3.1 \text{ Pg C}\cdot\text{year}^{-1}$ in additional releases of CO_2 and somewhat greater than $0.22 \text{ Pg C}\cdot\text{year}^{-1}$ in additional releases of CH_4 to the atmosphere (Table 2). These estimates should be regarded as a preliminary calculation to guide assessment of the potential significance of climate change impacts in these regions. The magnitudes of these computations are the same as the estimates of current release from tropical forest clearing (Houghton et al. 1985) and are one-fifth to one-half of the current release from combustion of fossil fuels (Marland et al. 1988).

There are many sources of uncertainty in these calculations, including uncertainties in the magnitude, and spatial and temporal heterogeneity of projected climate

Table 2. Estimates of increased net flux rate of carbon cycle gases from tundra and boreal ecosystems to the atmosphere

Ecosystem	Net Flux (Pg C·year ⁻¹)			
	Warm/wet		Warm/dry	
	CO ₂	CH ₄	CO ₂	CH ₄
Tundra	1.3	0.1	1.6	0.1
Boreal (Peatland + Upland)	0.03	0.12	0.83	0.12
Increased fire (Boreal Upland)	0.4	+	0.8	+
Total without fire	1.33	0.22	2.43	0.22
Total with fire	1.73	0.22+	3.23	0.22+

changes. Reducing these uncertainties is the activity of climate researchers. This report underscores the importance of obtaining accurate climate projections for extreme northern latitudes in order to determine the future operation of the global carbon cycle, even though economic impacts of climate change in these sparsely populated regions may not command the attention that must be paid to the economic impacts in temperate and tropical zones.

As explained in Section 1 of this report, the current development of climate model projections only allows us to develop estimates for the possible extremes or bounds of response of these ecosystems based on simplifying assumptions. In future assessment of climate change on the ecosystem dynamics of boreal and tundra regions, spatial and temporal aspects of climate change should be addressed.

The processes that control the release and uptake of CO₂ and CH₄ in arctic and boreal zones are poorly understood. They involve strong biotic feedbacks and are sensitive to environmental conditions, particularly to changes in the water table and to soil and air temperatures. The assumptions used in producing the calculations in Table 2, as explained in the previous section, are thought to emphasize the most significant processes determining carbon dynamics for a broad range of ecosystem types. They do not include many, possibly important processes such as changes in nutrient fluxes, direct effects of increased atmospheric CO₂ levels, changes in species composition and trophic structure. No data are currently available to confirm or

reject the calculations presented here. The next section outlines several possible short-term research projects that could provide preliminary data to fill this gap in knowledge until our understanding of carbon dynamics improves for high-latitude ecosystems.

3. REDUCING UNCERTAINTIES IN ECOSYSTEM RESPONSES

This section describes research projects that could, in 1 or 2 years that would significantly reduce the uncertainties in estimates of climate-induced changes in carbon balance in northern ecosystems. This list is not exhaustive; rather, it identifies areas for which additional information could contribute in very significant ways to determining the magnitude of critical processes affecting carbon balance changes, before commitments are made to long-term research.

3.1 DRAINAGE MANIPULATION: ROADS, DITCHES, AND VEHICLE TRACKS

Roads and drainage ditches have been built across many northern peatlands, producing dramatic changes in the local vegetation and hydrology (Heikurainen et al. 1978, Godwin 1978, Hutchinson 1980, Glaser et al. 1981, Glaser 1987). Boelter (1972), for example, showed that a deep ditch in northern Minnesota lowered the water table below the aerobic layer at horizontal distances up to 5 m from the ditch. Subsidence generally occurs within this zone as a result of (1) dewatering of pores and (2) enhanced decomposition as oxygen diffuses to greater depths within the profile (Stephens et al. 1984).

The impact of drawdown on the carbon balance of peatlands can thus be inferred from short-term measurements along transects that traverse both old and recently constructed drainage ditches. The horizontal and vertical extent of subsidence can be determined by critical leveling along these transects, and the loss of carbon from the peat profile can be estimated from present carbon flux measurements and stratigraphic determinations of carbon content as a function of both depth and time. Dating the uppermost 100 years of accumulation can be accomplished through ^{210}Pb and pollen markers, such as the *Ambrosia* rise that indicates the time of settlement. Productivity studies may be necessary to determine if the loss of carbon from a peat profile is partially compensated by a flush of vegetative growth on the drained peat surface associated with increased aerobic soil conditions and mineralization of nutrients from decomposing peat. Roads and vehicle tracks on tundra have a similar impact by obstructing drainage and lowering the water table on tundra, providing similar opportunities to monitor the impact of drawdown on carbon balance.

3.2 SAMPLING OF BURNED AND UNBURNED AREAS

Fire in the northern latitudes can liberate a substantial amount of carbon. The following comments apply to study of the taiga/boreal zone. Fires are not common in most tundra ecosystems, although this situation could be altered with climate changes.

In the taiga/boreal system, broadly speaking, there are two major types of ecosystems: uplands and peatlands. In addition, the effects of fire can be considered in both the short term (immediate release of CO_2 and CH_4 from combustion) and in the long term (effects of fire on ecosystem processes and carbon storage). Investigation of the role of fire in releasing carbon must consider both the difference in behavior between uplands and peatlands, and the difference between short-term and long-term effects.

In the uplands, short-term effects of fire can range from a simple charring of the surface of the forest floor and a possible consumption of needles within the crown of trees to almost complete oxidation of the forest floor and the consumption of a large part of the tree crown, including needles and branches up to 2 to 5 cm in diameter. This difference in fire intensity is related to the amount and the moisture content of fuel and to the weather conditions during the fire. Any post facto sampling must consider antecedent weather as an index to prefire fuel moisture, estimates of fuel loadings, and weather during the fire as important variables to be included in the data base.

The passage of a fire markedly changes the environment of the system. As a result of release of nutrients by direct oxidation during the fire, an increase in temperature due to removal of shading and blackening of the surface, an increase in surface pH through the formation of oxides of bases, and an increase in moisture content of the surface because of cessation of transpiration, microbial activity increases. Remaining organic material, both in the forest floor and in partially consumed vegetation (especially roots), is microbially oxidized much more rapidly than if the system had not burned. To quantify this effect, post facto sampling must include systems at various ages after burning. The short-term considerations must be overlaid on these long-term observations.

The peatlands present a contrasting situation. As in the uplands, short-term effects can vary. In the case of peatlands, the intensity of fire and the amount of organic matter that is oxidized depend not only on current weather but also on the

antecedent weather and its effect on water table depth. If the water table has been markedly lowered, fire can continue to smolder in deeper peat, even through the winter.

Long-term effects of fire on peatlands are usually not as prolonged as in uplands, because return to more normal water table depth (to nearer the surface) protects the unburned peat from microbial oxidation. If consumption of peat during the fire is deep enough, pools may actually form in the peatland where none previously existed. The unusual case of a continued low water table over the long term (perhaps not unusual under a scenario of climatic change) will lead to increased microbial oxidation, just as in the case of the uplands.

Finally, most fires do not completely cover any geographic area. Vagaries of weather, presence of rivers or lakes as fire breaks, absence of fuel, or other factors lead to occurrence of unburned patches within any burned landscape. Careful consideration of the cause of such patches may allow them to be used as controls or unburned comparisons in any post facto sampling. This must be done carefully; for example, an unburned patch whose direct cause is very low fuel loading would not be an acceptable control in comparison to systems where fuel loading is typically higher.

The amount of methane produced by the burning of biomass is related to the temperature of combustion. If it is possible to estimate combustion temperature based on environmental factors or the severity of the burn, then the amount of methane generated can be estimated from the procedure outlined by Rasmussen, Khalil, and Ward (unpublished data, 1988) and briefly described below.

The ratio of CO_2/CO is an index of the temperature of the burn. Hotter temperatures produce much less CO, thus increasing this ratio; cooler burns have a low ratio. For a CO_2/CO ratio less than 10, the average emission ratio of CH_4/CO_2 is 0.0125 ± 0.0006 . This is a dimensionless quantity as is the ratio of CO_2/CO . The \pm values are one standard error of the mean value. For hotter burns with CO_2/CO ratios greater than 10, the CH_4/CO_2 ratio is 0.0044 ± 0.0005 . The ratios are on a molar basis. For example, the ratio of CH_4/CO_2 at 0.0125 means that 0.0125 mole of CH_4 is emitted for every mole of CO_2 .

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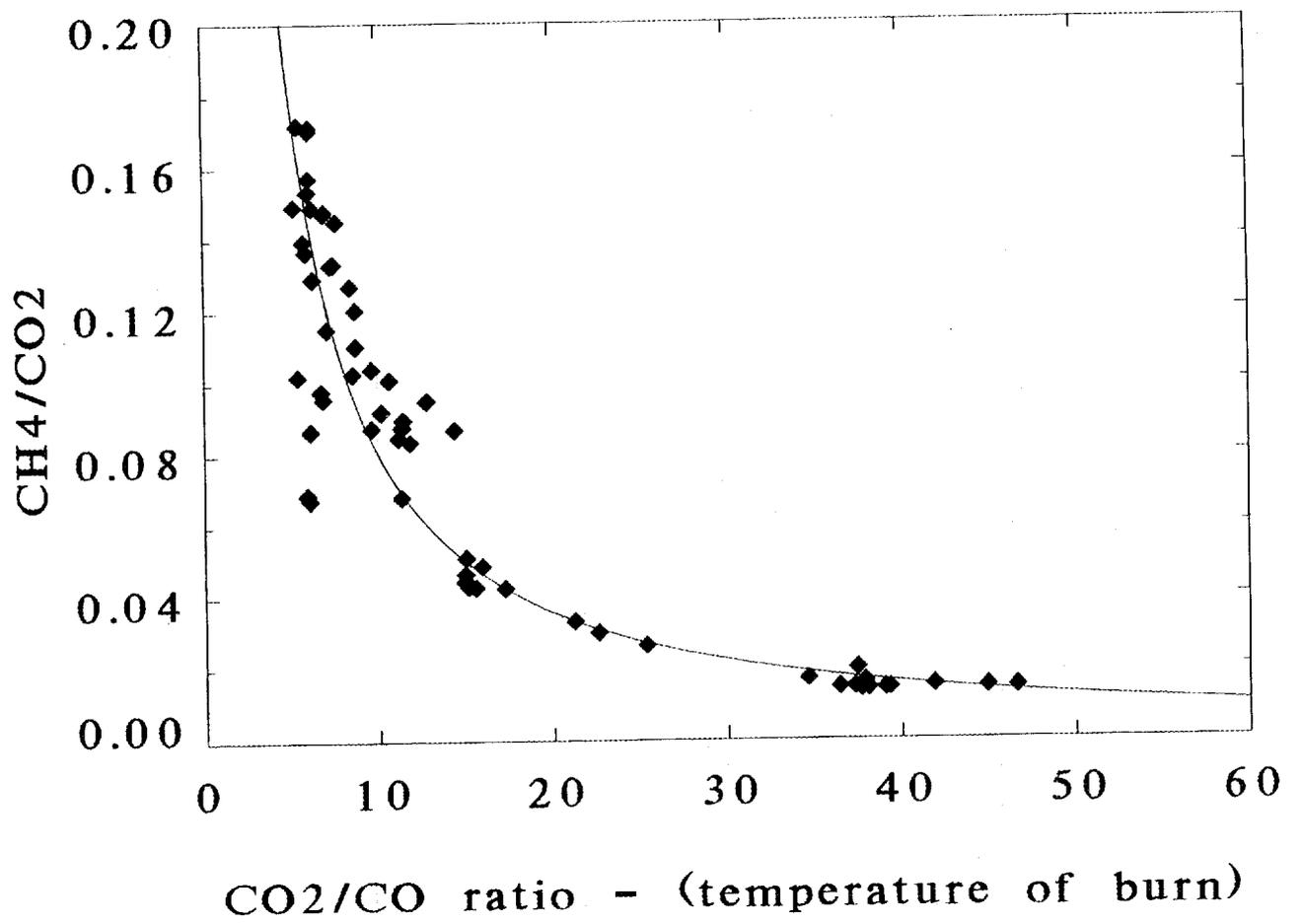


Fig. 4. Ratio of CH₄ emission to CO₂ from biomass burning as a function of the temperature index CO₂/CO (from Rasmussen, Khalil, and Ward, unpublished data).

Figure 4 shows the relationship more completely. The points are the data, and the solid line is an empirical power law fit of the form:

$$y = a \cdot x^b .$$

In this case, y is CH_4/CO_2 ratio, x is CO_2/CO ratio and a and b are fitted by least squares techniques; $a = 0.1187$ and $b = -1.17$. This formula can be used to estimate the average ratio y over any range of combustion temperatures.

3.3 PERMAFROST CO_2 AND CH_4 MEASUREMENTS

Two experiments can be conducted to determine the amount of trace gases trapped in permafrost. The first involves removing the upper layers of accumulated organic material and exposing an area of permafrost. Chambers would then be set up to determine the fluxes of CO_2 and CH_4 over the time of the year when new snow is not accumulating. It may be necessary to provide additional heat to accelerate the melting of the upper layers of the permafrost, or not, depending on the type of chamber used. In any case, simultaneous measurements of the air, soil, and permafrost temperatures would be needed. Such an experiment would provide a direct measure of the amount of CO_2 and CH_4 that can be expected to come if the earth warms from the continued buildup of CO_2 and trace gases and the subsequent melting of the upper layers of the permafrost.

The second experiment involves collecting a core of the permafrost material and melting it in the laboratory to determine the amount of CO_2 and CH_4 that is stored in it. This experiment would provide an estimate of the reservoir of CO_2 and CH_4 in the permafrost as a function of depth. These data would also provide an estimate of the climate feedback on the cycles of these gases and the additional emissions that may result; in addition, they would provide estimates of how long the additional fluxes can be sustained.

It is desirable to repeat both these experiments over many cases to assess the variability of CH_4 and CO_2 storage and flux from the high arctic permafrost. The two experiments are complementary and also provide a cross-check on the expected magnitudes of the temperature feedback for the fluxes of CO_2 and CH_4 from the arctic permafrost.

3.4 DEPTH MEASUREMENTS: PEAT AND UPLAND

Although the aerial extent of northern ecosystems has been mapped at various scales (Kivinen and Pakarinen 1978, Zoltai and Pollet 1983, Botch and Masing 1983,

Neustadt 1984, Matthews and Fung 1987), the carbon pool in these ecosystems must be estimated from relatively few depth measurements. The potentially largest carbon reservoirs, moreover, are the major peat basins, which have the fewest depth measurements because of inadequate access. Depth measurements from a few regions selected along climatic and geomorphic gradients will greatly complement the existing maps and provide a better estimate of the carbon pool and its potential response to a warming climate.

The possible response of these reservoirs to climatic change can be predicted from (1) estimates of past rates of carbon accumulation determined from peat profiles that have been dated by ^{14}C , (2) vertical profiles of methane and carbon dioxide within the peat, (3) the path of water flow within the peat profile (discharge, recharge, or horizontal flow), and (4) depth of the active layer in permafrost regions and acrotelm in peatlands or tundra.

3.5 GEOGRAPHIC TEMPERATURE ANALOGS

Peatlands are typically thought of as boreal ecosystems, covering extensive areas north of 45°N latitude. Especially in eastern North America, however, numerous relatively small *Sphagnum*- and *Polytrichum*-dominated peatlands exist both in glaciated and nonglaciated regions (e.g., Dachnowski 1912, Waksman 1942, Cameron 1968, 1970a,b,c, McDonald 1985). These peatlands are well below the southern limit of true raised bogs and as such, most are physiographically minerotrophic fens, receiving at least some inputs of water and nutrients from sources other than precipitation. Nonetheless, vegetationally and chemically, at least some of the Appalachian peatlands are comparable to their northern boreal counterparts (Wieder 1985).

Cameron (1968) states that all peat deposits in Appalachia are of Quaternary age, yet with decreasing latitude the peat deposits become progressively fewer in number, smaller in areal extent, thinner, and more highly decomposed. These southern peatland systems have persisted on the landscape under warmer climatic conditions than have prevailed in boreal regions. Pollen profiles with radiocarbon dates have been published for several southern peatland ecosystems (e.g., Sirkin et al. 1970, Maxwell and Davis 1972, Spear and Miller 1976, Watts 1979, Cotter 1983), but these data have generally not been interpreted from the perspective of geographical variation in rates of peat accumulation as influenced by geographical

22 *Reducing ecosystem uncertainties*

variation in temperature. A reinterpretation of these data for Appalachian peatlands may provide insights into the fate of present-day boreal peatland systems under a predicted global warming.

4. LONG-TERM RESEARCH

The available amount of basic knowledge on carbon cycling in boreal and arctic ecosystems with which to make reliable estimates of the carbon dynamics of these ecosystems under changing conditions is meager. While working on the calculations presented above, the workshop participants compiled an abbreviated list of the most important pieces of information that would be essential to constructing a more definitive estimate of CO₂ and CH₄ fluxes under a projected CO₂ induced climate change. This list is given here arranged roughly in decreasing order of priority.

1. Methods for determining soil respiration rates as functions of temperature, bulk density, carbon content and quality; role of humic inhibition and nutrient/carbon interactions, animal influences on decomposition dynamics, and aeration; and effects of permafrost dynamics, growing season length, and precipitation on soil aeration.
2. Understanding the coupling between landscape elements at two spatial scales. At a subregional scale, how climate change affects tundra thaw lake cycles; groundwater linkages between uplands and wetlands and between bogs and fens; water table influences from geomorphology; and effects of sea level changes on coastal ecosystems. At the regional to global scale, climate and vegetation interactions; how terrestrial hydrology and sea ice changes affect arctic ocean circulation and north Atlantic deep water formation; and the relationship between arctic ocean changes and circumpolar climate.
3. Determining ecosystem influences of nutrient cycle feedbacks, net primary production, and species composition changes on carbon storage and release.
4. Estimating the rate at which organic matter is converted to inactive or subfossil carbon and understanding the stratigraphic processes involved.

Obtaining this type of information will involve long-term and intensive research projects. The calculations given above of the possible increases in CO₂ and CH₄ fluxes under a twice ambient CO₂ climate, if they prove robust with more careful research, are large enough to warrant research programs to address these needs.

24 *Long-term research*

Essentially every federal agency involved in biogeochemical cycling and climate research has an interest in carbon dynamics in northern regions. The DOE Carbon Dioxide Research Division's Carbon Cycle Program must cooperate in developing long-term research programs with the appropriate agencies so that the northern terrestrial-atmosphere-ocean system can be better understood.

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REFERENCES

1. Boelter, D. H. 1972. Water table drawdown around an open ditch in organic soils. *Journal of Hydrology (Amst.)* 15:329-340.
2. Botch, M. S., and V. V. Masing. 1983. Mire ecosystems in the U.S.S.R. Pages 95-152. IN A. J. P. Gore (ed). *Mires: Swamp, Bog, Fen, and Moor, Volume 4B, Regional Studies*. Elsevier, New York.
3. Cameron, C. C. 1968. Peat. Pages 136-145. IN *Mineral Resources of the Appalachian Region*. U.S. Geological Survey Professional Paper 580.
4. Cameron, C. C. 1970a. Peat resources of the unglaciated uplands along the Allegheny Structural Front in West Virginia, Maryland, and Pennsylvania. U.S. Geological Survey Professional Paper 700-D:D153-D161.
5. Cameron, C. C. 1970b. Peat deposits of northeastern Pennsylvania. U.S. Geological Survey Bulletin 1317A:A1-A90.
6. Cameron, C. C. 1970c. Peat deposits of southeastern New York. U.S. Geological Survey Bulletin 1317B:B1-B32.
7. Clymo, R. S. 1984. The limits to peat bog growth. *Philosophical Transactions of the Royal Society of London* 303:605-654.
8. Cotter, J. F. P. 1983. The minimum age of the Woodfordian deglaciation of northeastern Pennsylvania and northwestern New Jersey. Ph.D. dissertation, Department of Geology, Lehigh University, Pennsylvania.
9. Dachnowski, A. 1912. Peat deposits of Ohio, their origin, formation, and uses: Ohio Geological Survey, 4th series, Bulletin 16. 424 pp.
10. Glaser, P. H., G. A. Wheeler, E. Gorham, and H. E. Wright, Jr. 1981. The patterned mires of the Red Lake Peatland, northern Minnesota: vegetation, water chemistry, and landforms. *Journal of Ecology* 69:575-599.
11. Glaser, P. H. 1987. The ecology of patterned boreal peatlands of northern Minnesota: A community profile. U.S. Fish and Wildlife Service Biological Report 85(7.14). 98 pp.
12. Godwin, H. 1978. *Fenland: Its Ancient Past and Uncertain Future*. Cambridge University Press, Cambridge. 196 pp.
13. Gorham, E. 1988. Biotic impoverishment in northern peatlands. IN G.M. Woodwell (ed.), *Biotic Impoverishment*. Cambridge University Press.
14. Grotch, S. L. 1988. Regional Intercomparison of General Circulation Model Predictions and Historical Climate Data. DOE/NBB-0084 TRO41. U.S. Department of Energy, Washington, D.C. 291 pp.
15. Heikurainen, L., K. Kenttamies, and J. Laine. 1978. The environmental effects of forest drainage. *Suo* 29:49-57.
16. Houghton, R. A., R. D. Boone, J. M. Melillo, C. A. Palm, G. M. Woodwell, N. Meyers, B. Moore, and D. L. Skole. 1985. Net flux of carbon dioxide from tropical forests in 1980. *Nature* 316:617-620.
17. Hutchinson, J. N. 1980. The record of peat wastage in the east Anglian Fenlands at Holme Post, 1848-1978 A.D. *Journal of Ecology* 68:229-249.

18. Kivinen, E., and P. Pakarinen. 1978. Geographical distribution of peat resources and major peatland complex types in the world. *Annales Academiae Scientiarum Fennicae Series A, III. Geologica-Geographica* 132:5-28.
19. Lachenbruch, A. H., and J. H. Marshall. 1986. Changing climate: Geothermal evidence from permafrost in the Alaskan Arctic. *Science* 234:689-696.
20. Marland, G., T. A. Boden, R. C. Griffin, S. F. Huang, P. Kanciruk, and T. R. Nelson. 1988. Estimates of CO₂ emissions from fossil fuel burning and cement manufacturing using the United Nations energy statistics and the U.S. Bureau of Mines cement manufacturing data. NDP030, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
21. Matthews, E., and I. Fung. 1987. Methane emission from natural wetlands: global distribution, area, and environmental characteristics of sources. *Global Biogeochemical Cycles* 1:61-86.
22. Maxwell, J. A., and M. B. Davis. 1972. Pollen evidence of Pleistocene and Holocene vegetation of the Allegheny Plateau, Maryland. *Quaternary Research* 2:506-530.
23. McDonald, B. R. 1985. Wetlands of West Virginia: Location and Classification. West Virginia Wildlife/Heritage Data Base. West Virginia Department of Natural Resources, Elkins, West Virginia.
24. Miller, P. C. (ed.) 1981. Carbon Balance in Northern Ecosystems and the Potential Effect of Carbon Dioxide Induced Climatic Change. Report of a Workshop, San Diego, California, March 7-9, 1980. CONF-8003118, U. S. Department of Energy, Washington, D.C. Available from National Technical Information Service, Springfield, VA 22161.
25. Neustadt, M. I. 1984. Holocene peatland development. Pages 201- 206. IN A. A. Velichko (ed.) and H. E. Wright, Jr. and C. W. Barnowsky (English eds.). Late Quaternary Environments of the Soviet Union. University of Minnesota Press, Minneapolis.
26. Olson, J. S. 1981. Carbon balance in relation to fire regimes. Pages 327-378. IN: H. A. Mooney, T. M. Bonnicksen, N. L. Christensen, J. E. Lotan, and W. E. Reiners (eds.), Fire Regimes and Ecosystem Properties. GTR WO-26, Forest Service, U.S. Department of Agriculture, Washington, D.C.
27. Post, W. M., J. Pastor, P. J. Zinke, and A. G. Stangenberger. 1985. Global patterns of soil nitrogen. *Nature* 317:613-616.
28. Schlesinger, M. E., and J. B. F. Mitchell. 1985. Model projections of the equilibrium climatic response to increased carbon dioxide. IN M. C. MacCracken and F. M. Luther (eds.), Projecting the Climatic Effects of Increasing Carbon Dioxide. DOE/ER-0237. U.S. Department of Energy, Washington DC.
29. Sirkin, L. A., J. D. Owens, J. P. Minard, and M. Rubin. 1970. Palynology of some Pleistocene peat samples from the coastal plain of New Jersey. U.S. Geological Survey Professional Paper 700D:D77-D87.
30. Spear, R. W., and W. G. Miller. 1976. A radiocarbon dated pollen diagram from the Allegheny Plateau of New York State. *Journal of the Arnold Arboretum* 57:369-403.

28 *References*

31. Stephens, J. C., L. H. Allen, Jr., and E. Chen. 1984. Organic soil subsidence. Pages 107–122. IN T. L. Holzer (ed.), *Man-Induced Land Subsidence, Reviews in Engineering Geology, Volume VI*. Geological Society of America, Boulder, Colorado.
32. Waksman, S. A. 1942. *The peats of New Jersey and their utilization*. New Jersey Department of Conservation and Development. Geological Series Bulletin 55. 155 pp.
33. Watts, W. A. 1979. Late Quaternary vegetation of central Appalachia and the New Jersey Coastal Plain. *Ecological Monographs* 49:427–469.
34. Wieder, R. K. 1985. Peat and water chemistry at Big Run Bog, a peatland in the Appalachian Mountains of West Virginia. *Biogeochemistry* 1:277–302.
35. Zoltai, S. C., and F. C. Pollet. 1983. Wetlands of Canada: their classification, distribution, and use. Pages 245–268. IN A. J. P. Gore (ed.), *Mires: Swamp, Bog, Fen, and Moor, Volume 4B: Regional Studies*. Elsevier, New York.

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