



CO₂ and CH₄ exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st century

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[1] Terrestrial ecosystems of the northern high latitudes (above 50°N) exchange large amounts of CO₂ and CH₄ with the atmosphere each year. Here we use a process-based model to estimate the budget of CO₂ and CH₄ of the region for current climate conditions and for future scenarios by considering effects of permafrost dynamics, CO₂ fertilization of photosynthesis and fire. We find that currently the region is a net source of carbon to the atmosphere at 276 Tg C yr⁻¹. We project that throughout the 21st century, the region will most likely continue as a net source of carbon and the source will increase by up to 473 Tg C yr⁻¹ by the end of the century compared to the current emissions. However our coupled carbon and climate model simulations show that these emissions will exert relatively small radiative forcing on global climate system compared to large amounts of anthropogenic emissions.

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1. Introduction

[2] Tundra, woodland and forest ecosystems of the northern high latitudes (north of 50°N) contain about one-quarter of the globe's terrestrial organic carbon, much of which is in the soil [Gorham, 1991; Schlesinger, 1997]. Soil carbon is sensitive to climate changes, with the potential for accelerating soil microbial processes leading to increased emissions of CO₂ and CH₄ to the atmosphere in a warmer and wetter future [Melillo *et al.*, 1990; Prentice *et al.*, 2001; Webster *et al.*, 2003; ACIA, 2004; Davidson and Janssens, 2006].

[3] There are no existing budgets for the combined fluxes of CO₂ and CH₄ between the terrestrial ecosystems of the region and the atmosphere for either current or future

conditions [ACIA, 2004]. Estimates of the annual net CO₂ balance for the northern high latitudes during the 1990s indicate the region functioned as a sink of several hundred teragrams of carbon per year [e.g., Schimel, 1995; Myneni *et al.*, 2001; Gurney *et al.*, 2004]. For CH₄ there is general agreement that the region is currently a source of this potent greenhouse gas, although its magnitude is poorly defined [e.g., Roulet *et al.*, 1994; Christensen *et al.*, 1996; Cao *et al.*, 1996]. How the combined CO₂ and CH₄ budget for the region will change over the 21st century depends on the complex responses of northern high latitude ecosystems to changes in climate, atmospheric CO₂ concentration and disturbance regimes, especially permafrost thawing and fires [Romanovsky and Osterkamp, 1997; Schulze *et al.*, 1999; Cramer *et al.*, 2001; Zhuang *et al.*, 2002, 2003, 2004; van der Werf *et al.*, 2003].

[4] In this study, we use a process-based biogeochemistry model, the Terrestrial Ecosystem Model (TEM) [Melillo *et al.*, 1993; Zhuang *et al.*, 2002, 2003, 2004] to estimate the net CO₂ and CH₄ fluxes between land ecosystems and the atmosphere that result from ecosystem metabolism. Our estimate of net CO₂ flux is based on the balance between the simulated net uptake of CO₂ associated with net primary production by plants and the simulated release of CO₂ associated with decomposition of organic matter. This net CO₂ flux estimate includes the consequences of fire for carbon release during burning and carbon uptake during vegetation regrowth following fire [Zhuang *et al.*, 2002]. It also includes the decomposition of newly available soil organic matter associated with thawing permafrost. Our estimate of net CH₄ flux is based on the balance between simulated net CH₄ emissions from wetland soils and simulated CH₄ consumption by upland soils [Zhuang *et al.*, 2004]. The structure, parameterization, calibration and performance of this version of TEM and spatially-explicit data on vegetation distribution, elevation, soil texture, soil-water pH, wetland distribution, and fractional inundation of wetlands used in this study are well documented [Melillo *et al.*, 1993; Zhuang *et al.*, 2002, 2003, 2004].

2. Methods

[5] We conduct six “core” experiments by running the model twice for each of three plausible climate scenarios, once with a CO₂ fertilization effect on photosynthesis, and once without. For the “no CO₂ fertilization” cases, we run the model so that the climate changes over the century in each of the three scenarios, but we fix the atmospheric CO₂ concentration at 370 ppm, which is the mole fraction that we used to model the current condition, for carbon uptake by vegetation. In all six core experiments, we include

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considerations of fire disturbance and thawing permafrost in response to climate change. In each simulation, TEM estimates the terrestrial carbon and nitrogen dynamics of each 0.5° latitude x 0.5° longitude grid cell from 1860 to 2100. Each simulation uses the same historical climate generated by the MIT-IGSM from 1860 to 1990, but then uses the results from the alternative climate projections from 1991 to 2100.

[6] A three-step process is used to initialize carbon and nitrogen pools within a grid cell for 1860. First, TEM is run until equilibrium conditions are reached for an undisturbed ecosystem using the long-term averaged climate and CO₂ concentrations from 1860 to 1899. Then, the model uses the climate from 1860 to 1899 repeated three times to account for the influence of climate interannual variability on the initial conditions of the undisturbed ecosystem. To account for the influence of pre-1860 fire disturbances on initial conditions, the model continues to use the climate from 1860 to 1899 repeated five times, but now assumes that 1/150th of the area of each grid cell is burned each year. From 1860 to 2000, 1/150th of the area of each grid cell is assumed to burn each year unless otherwise indicated by information in historical fire data sets (years 1950 to 2003 in Alaska [French *et al.*, 2003, 2004], 1959 to 1999 in Canada [Amiro *et al.*, 2001], 1996 to 2002 in Russia [Soja *et al.*, 2004a, 2004b], and 1997 to 2001 in the remainder of land area north of 50°N [van der Werf *et al.*, 2003]), in which case, 1/150th of the remaining portion is burned each year. If the historical fire data sets indicate the occurrence of a fire in a grid cell, the burned area does not burn again during the simulation based on an assumed fire return interval of 150 years as determined from previous studies in the region [e.g., Kasischke *et al.*, 1995]. Otherwise, the area burned each year in each grid cell is assumed to increase by 1% per year after 2000 such that the area burned in 2100 is twice that burned in 2000 (100% increase). This rate is consistent with an assessment that area burned in the study region will increase by 80% over the next century [ACIA, 2004]. The magnitude and partitioning of fire emissions among CO₂ and CH₄ are based on the approach of French and others [French *et al.*, 2003, 2004] using estimates of vegetation carbon and soil organic carbon simulated by TEM. We estimate the newly available soil organic carbon at different soil depths due to permafrost thawing based on the simulated active layer depth and soil carbon distribution profile for tundra and boreal forest ecosystems [Jobbágy and Jackson, 2000].

[7] The monthly estimates of surface air temperature, precipitation, and vapour pressure for the three future climate and atmospheric CO₂ concentration scenarios are obtained by mapping the projected zonal-average changes with MIT's Integrated Global Systems Model (IGSM) [Reilly *et al.*, 1999; Prinn *et al.*, 1999; Webster *et al.*, 2003] to latitude and longitude by adjusting observed current climate [Xiao *et al.*, 1997, 1998; Euskirchen *et al.*, 2006]. Each of the scenarios is based on a specific set of assumptions regarding anthropogenic emissions of greenhouse gases and air pollutants, climate sensitivity, ocean diffusivity; and aerosol forcing and together defines a 90% probability range for global mean temperature change in 2100 based on a 250 member ensemble of projections assuming no explicit climate policy [Webster *et al.*, 2003].

The annual anthropogenic CO₂ emissions in 2100 for the three scenarios are equivalent to 128, 73 and 23 Pg CO₂ for the “High,” “Intermediate” and “Low” cases, respectively. These emissions correspond to projected atmospheric CO₂ mole fraction (parts per million, ppm) by 2100 of about 1152 ppm, 694 ppm, and 481 ppm, respectively. Air temperatures in the region are projected to increase by 2 to 7°C and annual precipitation is projected to increase by 20 to 121 mm.

[8] In addition to climate change and CO₂ fertilization, there are large uncertainties about how fire disturbance may influence future carbon dynamics. To explore the potential importance of these uncertainties, we conduct a series of additional TEM simulations. To explore the sensitivity of carbon fluxes from this region to fire disturbance, the six core simulations are rerun twice under assumptions that burned areas increased by either 50% (Low-fire) or 150% (High-fire) by year 2100 compared to the current fire regime rather than the 100% increase assumed in the six core simulations.

[9] To estimate how the changes in high latitude carbon emissions influence the greenhouse gas burden and their global warming effects on the global climate system during the 21st century, we conduct another six IGSM simulations that incorporate the changes in regional net terrestrial fluxes of CO₂ and CH₄ from the six “core” experiments and compare the results of these simulations with a “control simulation”, which assumes that high latitude greenhouse gas emissions stay constant at 1990 levels. This approach allows us to consider the influence of lifetime changes in atmospheric CO₂ and CH₄ concentrations associated with changes in atmospheric chemistry (e.g., hydroxyl radical) and climate in addition to uptake by oceans and terrestrial ecosystems in other regions when estimating radiative forcing effects.

3. Results and Discussion

[10] Under present climate conditions, we estimate that northern high-latitude land ecosystems are a small net source of 276 Tg C yr⁻¹. Of this total, 240 Tg C yr⁻¹ is as CO₂ and 36 Tg C yr⁻¹ is as CH₄. The CO₂ emissions are mostly from forest fires (213 Tg C yr⁻¹), while the CH₄ emissions are mostly from methane-producing bacteria in the major wetlands of the region. Our estimate of a small high-latitude CO₂ source is within the ± 1σ interval of the standard inversion results of carbon flux history for this region during the last few years of the 20th century [e.g., Ciais *et al.*, 1995; Bousquet *et al.*, 1999; Gurney *et al.*, 2002; Rödenbeck *et al.*, 2003]. For CH₄, our estimate is at the low end of the range (31 to 106 Tg CH₄ yr⁻¹) reported in other recent studies [e.g., Potter, 1997; Cao *et al.*, 1998; Walter *et al.*, 2001; Chen, 2004].

[11] For the 21st century, our simulations indicate that the sign and the magnitude of the cumulative carbon flux between land ecosystems and the atmosphere vary according to what is assumed about (1) CO₂ fertilization of photosynthesis; (2) changes in the area burned over the century; and (3) the level of anthropogenic emissions associated with fossil fuel burning (Table 1). Without a CO₂ fertilization effect, our simulations show a northern high-latitude land source of between about 34 and 54 Pg C

over the 21st century. With a CO₂ fertilization effect, and with either low or intermediate levels of anthropogenic C emissions, our simulations show a northern high-latitude source of between about 5 and 33 Pg C over the 21st century. The net carbon losses from these ecosystems are the result of an increased rate of soil respiration with warming, an increase in the area burned over the century, and an increased amount of soil organic matter susceptible to decay with permafrost thaw. Net carbon losses over the 21st century due to fires range from 20 to 30 Pg, while losses associated with permafrost thawing range from 7 to 17 Pg C over the 100-years.

[12] For different future fire disturbance scenarios, under the assumption of existing persistent CO₂ fertilization effects on vegetation carbon uptake, the region acts as a source of 4.6 to 33.4 Pg C over the 21st century under low and intermediate levels of anthropogenic C emissions and as a sink of 4.9 to 24.1 Pg C under a high level of anthropogenic emissions (Table 1). If there is no persistent CO₂ fertilization effect on photosynthesis with increasing atmospheric CO₂ concentrations, the region will act as a stronger source of 34.4 to 54.1 Pg C over the 21st century. Fire carbon emissions are not linearly related to area burned in the various scenarios. The reduced disturbance in the low-fire scenario allows more carbon to accumulate in the ecosystem so that more carbon is released per fire event. As a result, the carbon emissions from the low-fire scenario are about the same as the emissions from the intermediate-fire scenario over the 21st century. In contrast, the enhanced disturbance in the high-fire scenarios reduces carbon stocks in the ecosystem so that less carbon is released per fire event. These results suggest that future fire emissions will depend on the ecosystem response to historical fire regimes.

[13] The thawing of permafrost has been identified as an important mechanism for the release of both CO₂ and CH₄ to the atmosphere over the coming centuries. *Davidson and Janssens* [2006] indicate that the potential loss of carbon over the 21st century from permafrost thawing is 100 Pg C. The high end of our estimates is between five and six times lower. Our estimate does not include the complex interactions among thermokarst dynamics, fires and changing hydrology in wetlands and peatlands [*Jorgenson et al.*, 2001; *Zimov et al.*, 2006]. These interactions could lead to higher carbon emissions than we have simulated.

[14] By contrast, under a high level of anthropogenic C emissions and CO₂ fertilization, our simulations show a land sink for the region of between about 5 and 24 Pg C

Table 1. Cumulative Net Carbon Fluxes Between the Land Ecosystems of the High Northern Latitudes and the Atmosphere Over the 21st Century^a

Rate of Increase in Area Burned		Net C Flux (Pg C)		
		Low Emissions	Intermediate Emissions	High Emissions
50%	CO ₂ fertilization	23.37	4.60	-24.13
	No CO ₂ fertilization	37.07	39.28	34.38
100%	CO ₂ fertilization	25.00	13.34	-14.49
	No CO ₂ fertilization	44.90	46.71	42.18
150%	CO ₂ fertilization	33.43	22.10	-4.86
	No CO ₂ fertilization	52.75	54.12	49.98

^aUnits are Pg C per century. Negative numbers represent net fluxes of carbon from the atmosphere to the land.

Table 2. Changes in CO₂ and CH₄ Concentrations and Global Radiative Forcing (F) Over the 21st Century Associated With Climate-Related Biogeochemical Changes in the High Northern Latitudes

Anthropogenic Emissions	CO ₂ Fertilization Effect			No CO ₂ Fertilization Effect		
	Δ[CH ₄], ppm	Δ[CO ₂], ppm	ΔF, W/m ²	Δ[CH ₄], ppm	Δ[CO ₂], ppm	ΔF, W/m ²
High	0.35	-19	-0.065	0.25	0.7	0.047
Intermediate	0.18	-5.1	-0.006	0.15	3.3	0.073
Low	0.06	-1.6	-0.005	0.05	2.1	0.044

over the 21st century (Table 1). For these cases, the net gain of carbon over the 21st century occurs, at least in part, because the warming of soils makes more nitrogen available to plants and thereby enables them to be more responsive to the higher levels of CO₂ [*Melillo et al.*, 2002].

[15] Methane fluxes are included in the total carbon fluxes reported in Table 1. Our simulations show that the northern high latitude wetlands will function as a source of between 4.1 and 5.8 Pg C over the century. By 2100, we project CH₄ emissions from the wetlands of the region would more than double over the century when anthropogenic emissions are high. Using a simulation modeling approach, *Gedney* and colleagues [*Gedney et al.*, 2004] have also estimated a projected doubling of CH₄ emissions over this century. The thawing of permafrost and CO₂ fertilization of plants stimulates CH₄ emissions from high-latitude wetlands because both increase the amount of carbon substrate available to the methane-producing bacteria.

[16] The estimated loss of approximately 50 Pg C from northern high latitude terrestrial ecosystems for some of our simulations without CO₂ fertilization translates to a loss of approximately 1000 g C m⁻² during the 21st Century. If all of this carbon goes into the atmosphere as CO₂, it would translate to a per area contribution of approximately 3 W m⁻² century⁻¹ (0.3 W m⁻² decade⁻¹) forcing based on the assumption that 1 W m⁻² forcing is equivalent to a net loss of in 311 g C m⁻² across the entire surface of the earth (*E. S. Euskirchen et al.*, Energy feedbacks to the climate system due to reduced high-latitude snow cover during 20th century warming, manuscript in preparation, 2006; hereinafter referred to as *Euskirchen et al.*, manuscript in preparation, 2006). This degree of forcing is comparable to the per area forcing of 9 W m⁻² for the conversion of sedge tundra to shrub tundra over three centuries and of 26 W m⁻² for the conversion of sedge tundra to boreal conifer forest over nine centuries [*Chapin et al.*, 2005], but is small in comparison to the estimate of 2 W m⁻² decade⁻¹ forcing associated with earlier snowmelt in recent decades (*Euskirchen et al.*, manuscript in preparation, 2006).

[17] While the local-scale changes in forcing associated with carbon stock changes can be of the same order of magnitude as potential changes in vegetation, the changes in forcing at the global scale must account for the effects of fluxes of CO₂ and CH₄ from northern high latitudes terrestrial ecosystems on atmospheric concentrations of CO₂ and CH₄ in the context of fossil fuel emissions and other sources and sinks of these gases [*Hansen et al.*, 2000;

¹Auxiliary materials are available at <ftp://ftp.agu.org/apend/gl/2006gl026972>.

Frolking *et al.*, 2006]. In contrast to local-scale changes in carbon stocks, a fully coupled analysis we conducted indicates that the global-scale forcing due to the carbon stock changes in northern high latitude terrestrial ecosystems will play a minor role in feedback to the global climate system over the 21st century. We estimate that the change in global radiative forcing associated with climate-related biogeochemical changes in the high northern latitudes will be less than $\pm 0.1 \text{ W m}^{-2}$ over the course of the 21st Century regardless of the details of scenarios (Table 2; auxiliary material Tables S1–S6).¹ This occurs because the changes in carbon storage are small in comparison with the cumulative fossil fuel emissions in the 21st Century. For example, a 50 Pg C change in carbon storage is only about 3% of the approximately 1500 Pg C fossil fuel emissions in the low emissions scenario.

[18] To improve our estimates of the interactions of climate change and the biogeochemical feedbacks to the climate system from northern high latitude ecosystems, we need better information in three areas: (1) effects of CO₂ fertilization on net primary production and net ecosystem production in the region; (2) the fire history of forests in the region and what controls the spatial and temporal patterns of this important disturbance; and (3) the linkages between a dynamic hydrology, lake formation and drainage, and permafrost thawing. Each of these topics is researchable and should be vigorously pursued to enhance our understanding of the dynamics of the earth system and to provide clear guidance for climate-change policy.

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