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The role of historical fire disturbance in the carbon dynamics of the pan-boreal region: A process-based analysis

M. S. Balshi,[1] A. D. McGuire,[2] Q. Zhuang,[3] J. Melillo,[4] D. W. Kicklighter,[4] E. Kasischke,[5] C. Wirth,[6] M. Flannigan,[7] J. Harden,[8] J. S. Clein,[9] T. J. Burnside,[9] J. McAllister,[9] W. A. Kurz,[10] M. Apps,[10] and A. Shvidenko[11]

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[1] Wildfire is a common occurrence in ecosystems of northern high latitudes, and changes in the fire regime of this region have consequences for carbon feedbacks to the climate system. To improve our understanding of how wildfire influences carbon dynamics of this region, we used the process-based Terrestrial Ecosystem Model to simulate fire emissions and changes in carbon storage north of 45°N from the start of spatially explicit historically recorded fire records in the twentieth century through 2002, and evaluated the role of fire in the carbon dynamics of the region within the context of ecosystem responses to changes in atmospheric CO_2 concentration and climate. Our analysis indicates that fire plays an important role in interannual and decadal scale variation of source/sink relationships of northern terrestrial ecosystems and also suggests that atmospheric CO_2 may be important to consider in addition to changes in climate and fire disturbance. There are substantial uncertainties in the effects of fire on carbon storage in our simulations. These uncertainties are associated with sparse fire data for northern Eurasia, uncertainty in estimating carbon consumption, and difficulty in verifying assumptions about the representation of fires that occurred prior to the start of the historical fire record. To improve the ability to better predict how fire will influence carbon storage of this region in the future, new analyses of the retrospective role of fire in the carbon dynamics of northern high latitudes should address these uncertainties.

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1. Introduction

[2] Terrestrial ecosystems in high latitudes contain large reserves of carbon [*McGuire et al.*, 2002, 2006]. Wildfire is a common disturbance that affects the structure and function of ecosystems in the region [*McGuire et al.*, 2006]. Pronounced warming in high latitudes, which has been occurring for the past several decades [*Chapman and Walsh*, 1993; *Serreze et al.*, 2000; *Serreze and Francis*, 2006; *McGuire et al.*, 2006], is altering the fire regime of the region [*Gillett et al.*, 2004; *Kasischke and Turetsky*, 2006] and has consequences for carbon storage of northern ecosystems [*Kasischke et al.*, 1995; *Stocks et al.*, 1998; *Flannigan et al.*, 2005]. While many studies have focused on using fire observation data to estimate fire emissions in northern high latitudes [*Conard and Ivanova*, 1997; *French et al.*, 2000; *Shvidenko and Nilsson*, 2000; *Kajii et al.*, 2002; *Conard et al.*, 2002; *Kasischke and Bruhwiler*, 2002; *Potter et al.*, 2003a; *Soja et al.*, 2004; *Yurganov et al.*, 2004; *Kasischke et al.*, 2005], understanding the role of fire on carbon dynamics in this region requires consideration of several additional factors.

[3] The state of the landscape, or stand age distribution across the landscape before a fire event occurs is one of the factors that influences carbon dynamics [*Kurz and Apps*, 1999; *Chen et al.*, 2002, 2003]. Stand age distributions in fire-prone systems are directly affected by the historical patterns of fire across the landscape. Although data sets exist that provide an historical picture of fires across the

[1]Department of Biology and Wildlife, University of Alaska Fairbanks, Fairbanks, Alaska, USA.
[2]Alaska Cooperative Fish and Wildlife Research Unit, U.S. Geological Survey, University of Alaska Fairbanks, Fairbanks, Alaska, USA.
[3]Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana, USA.
[4]Ecosystems Center, Marine Biological Laboratory, Woods Hole, Massachusetts, USA.

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[5]Department of Geography, University of Maryland at College Park, College Park, Maryland, USA.
[6]Max-Planck-Institute for Biogeochemistry, Jena, Germany.
[7]Great Lakes Forestry Centre, Canadian Forest Service, Sault Ste. Marie, Ontario, Canada.
[8]U.S. Geological Survey, Menlo Park, California, USA.
[9]Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, Alaska, USA.
[10]Natural Resources Canada, Canadian Forest Service, Victoria, British Columbia, Canada.
[11]International Institute for Applied Systems Analysis, Laxenburg, Austria.

landscape, estimating the effects of fire on carbon dynamics requires that fires are accounted for prior to the start of the historical record [*McGuire et al.*, 2004]. While several studies have used fire cycle information to account for recurring fires, they generally do not explicitly consider the history of fire across the landscape [e.g., *Thonicke et al.*, 2001; *Venevsky et al.*, 2002].

[4] Another important factor to consider when estimating the effects of fire on carbon dynamics is influence of burn severity, which can be defined as the fractional amount of carbon consumed during a fire from both aboveground and ground layer biomass [*Kasischke et al.*, 2005]. Burn severity is highly variable in northern ecosystems, and depends on the time of the year in which the fire occurs [*Kasischke et al.*, 1995, 2000], amount of fuel [*Furyaev*, 1996], spatial heterogeneity of vegetation and topography across the landscape [*Turner and Romme*, 1994], and weather conditions at the time of fire [*Johnson*, 1992]. As a result, representing burn severity across large spatial scales has proven to be difficult and is typically associated with a particular vegetation type or ecoregion [*French et al.*, 2002]. Furthermore, the amount of carbon consumed on a per-fire basis can differ with respect to the type of fire regime, which is defined by the intensity, frequency, seasonality, size, and type of fire [*Weber and Flannigan*, 1997]. In the North American boreal forest fires are predominantly stand-replacing and characterized by a high-intensity crown fire regime [*Johnson*, 1992]. Fires that occur across boreal Eurasia range from low-intensity surface fires (e.g., Siberian Scots pine stands) to high-intensity crown fires that dominate boreal needle-leaf, larch (deciduous conifer), and pine stands (evergreen conifer) [*Conard and Ivanova*, 1997; *Wirth et al.*, 2002a].

[5] To understand the role of fire in the carbon dynamics of northern ecosystems, it is also important to evaluate changes in fire disturbance in the context of other environmental changes. While several studies have been conducted that incorporate the influence of fire on carbon dynamics in the context of forest inventory data [*Kurz and Apps*, 1999; *Shvidenko and Nilsson*, 2002, 2003; see also *Myneni et al.*, 2001], these studies do not explicitly consider the effects of other environmental factors such as changes in atmospheric CO_2 and climate. Process-based models are designed to evaluate how changes in climate and environmental chemistry influence carbon dynamics, and simulations can be conducted to quantify the effect of individual factors [*McGuire et al.*, 2001]. Process-based models also complement estimates of regional carbon storage made by atmospheric inversion models [*Schimel et al.*, 2001; *Dargaville et al.*, 2002, 2006; *Gurney et al.*, 2004], which collectively can identify uncertainties in the net exchange between the earth's surface and the atmosphere, but are not able to evaluate the mechanisms responsible for the exchanges.

[6] Several process-based studies have been conducted that incorporate the influence of disturbance on carbon dynamics but focus primarily on its response to land-use change [*McGuire et al.*, 2001] or regional fire regimes [*Peng and Apps*, 1999; *Amiro et al.*, 2000; *Venevsky et al.*, 2002; *Chen et al.*, 2000, 2003]. Other process-based studies have used the satellite record to infer disturbance, but have not explicitly considered the role of fire dynamics prior to the start of the satellite record [e.g., *Potter et al.*, 2003a, 2003b, 2005]. *Mouillot et al.* [2006] used a process-based model to estimate fire emissions, but do not estimate the overall effect of fire on the carbon budget. To our knowledge, a study conducted by *Zhuang et al.* [2006] is the only analysis that uses a process-based approach to simulate the effects of fire on northern ecosystems using historical fire records. However, *Zhuang et al.* [2006] did not consider how carbon dynamics are influenced by spatial variability in burn severity and spatial variability in fire frequency prior to the start of the historical record. The observed changes in climate [*Chapman and Walsh*, 1993; *Serreze et al.*, 2000] and the potential for a changing climate to alter future fire regimes of northern high latitudes [*Wotton and Flannigan*, 1993; *Flannigan et al.*, 1998; *Kasischke et al.*, 1995; *Stocks et al.*, 1998; *Wotton et al.*, 2003; *Flannigan et al.*, 2005; *McCoy and Burn*, 2005] suggest that it is important to project how future changes in carbon dynamics respond to changes in the fire regime. Our ability to make projections of future changes in carbon dynamics of northern ecosystems is limited by our understanding of how the temporal and spatial aspects of fire influence historical carbon dynamics.

[7] The focus of this study is to improve our understanding of the role of historically recorded fire on carbon dynamics in ecosystems of northern high latitudes north of 45°N (referred to hereafter as the "pan-boreal region"). In particular, our objectives are to estimate fire emissions and changes in carbon storage in the pan-boreal region, to evaluate the role of historically recorded fire in carbon dynamics of the region in the context of ecosystem responses to changes in atmospheric CO_2 concentrations and climate, and to identify sources of uncertainty that should be reduced in retrospective analyses of the role of fire in the carbon dynamics of the pan-boreal region. In comparison to a previous study by *Zhuang et al.* [2006], our analysis considers how carbon dynamics are influenced by spatial variability in burn severity and by spatial variability in fire frequency prior to the start of the historical record of fire in terrestrial ecosystems of northern high latitudes. We also identify key sources of uncertainty that should be reduced in order to better understand the role of fire in the carbon dynamics of the pan-boreal region.

2. Methods

2.1. Overview

[8] In this study we evaluate how changes in atmospheric CO_2 concentration, climate, and fire influence carbon dynamics for North America and Eurasia north of 45°N using the process-based Terrestrial Ecosystem Model (TEM). The advantage of using a process-based model for simulating carbon dynamics is that individual processes that affect carbon storage can be isolated. To initialize our simulations we first run the model to equilibrium (annual net primary production = annual heterotrophic respiration) in year 1000 for each terrestrial 0.5° (latitude by longitude) grid cell north of 45°N using the mean monthly climate from 1901–1930. We then conduct a 900 year spin-up (from year 1001–1900) to dynamically equilibrate the model to the fire regime and to multidecadal variability in the climate. During the spin-up period, climate for the period 1901–1930 is repeated. A backcasting approach (see section 2.4)

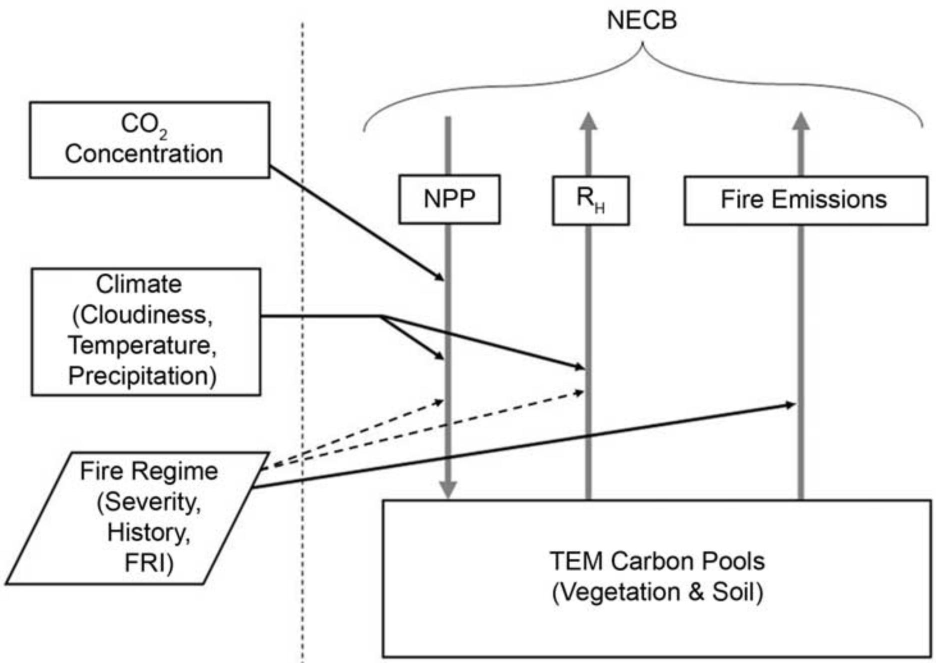

Figure 1. The simulation framework of this study in which the Terrestrial Ecosystem Model (TEM) was used to simulate the effects of fire on carbon dynamics. Input data sets include CO_2 concentration, cloudiness, air temperature, precipitation, and spatially explicit information on fire history (area burned), burn severity (carbon fraction consumed during a fire event), and fire return interval (FRI, used for inserting fires prior to the historical record). Burn severity parameters, fire history, and FRI are used to calculate fire emissions from TEM carbon pools (vegetation and soil carbon). Fire regime also has indirect effects on net primary production (NPP) and heterotrophic respiration (R_H) through the influence on soil and vegetation carbon pools. Model outputs are NPP, R_H, and fire emissions which are used to calculate the net ecosystem carbon balance (NECB).

is used to account for the influence of fire on carbon dynamics (including the spin-up period) before 1959 for North America and before 1996 for Eurasia. The model is then run from year 1901–2002 using gridded monthly climate based on observations (see section 2.3). In this study, we conduct two sets of simulations. In the first set of simulations, photosynthesis is sensitive to increasing atmospheric CO_2 concentrations (a CO_2 fertilization effect), while in the second set photosynthesis is not sensitive to increasing atmospheric CO_2 concentrations. For the set considering the effect of atmospheric CO_2 fertilization we conduct three simulations. In simulation one (S1), atmospheric CO_2 concentration is allowed to vary, but a mean monthly climate from 1901–1930 is used to represent climate for each year (i.e., "constant climate") and no fire disturbances are assumed to occur. In simulation two (S2), both atmospheric CO_2 concentration and climate are allowed to vary, but again, no fire disturbances are assumed to occur. In simulation three (S3), atmospheric CO_2 concentration and climate are allowed to vary and fire disturbances are assumed to occur. For the second set of simulations we conduct the same three simulations as described in the first set, but with atmospheric CO_2 fixed at 296 ppm, which is the mole fraction used to initialize each simulation. We then analyze our simulation results for the periods of historically recorded fire disturbance, which are 1959–2002 in boreal North America and 1996–2002 in the pan-boreal region. The effect of CO_2 fertilization on carbon storage is determined by the results of the S1 simulation. The effect of climate on carbon storage is determined as the difference in results between the S2 and S1 simulations. Similarly, the effect of fire on carbon storage is determined as the difference in results between the S3 and S2 simulations.

2.2. Terrestrial Ecosystem Model (TEM)

[9] The TEM is a large-scale, process-based biogeochemical model that estimates monthly pools and fluxes of carbon and nitrogen for land-based areas. The model is coupled to a soil thermal model and can be applied on both permafrost and nonpermafrost soils [*Zhuang et al.*, 2003]. The TEM is driven by a series of spatially explicit data sets that include climate, elevation, soil texture, and vegetation. The equations and parameters of TEM have been documented in previous studies [*Raich et al.*, 1991; *McGuire et al.*, 1992; *Tian et al.*, 1999; *Zhuang et al.*, 2003; *Euskirchen et al.*, 2006]. The model has been applied previously to various regions across the globe including northern ecosystems [e.g., *McGuire et al.*, 2000a, 2000b, 2001, 2002, 2004; *Clein et al.*, 2000, 2002; *Zhuang et al.*, 2001, 2002, 2003; *Euskirchen et al.*, 2006]. Our application of TEM to this study is based on version 5.1 of the model [see *Euskirchen et al.*, 2006], which has been modified in this study to incorporate the effects of fire (Figure 1). Several of the

parameters within TEM are defined based on values obtained from the peer-reviewed literature. However, the rate limiting parameters are defined by calibrating the model to pools and fluxes of field sites representative of particular ecosystems (e.g., tundra and boreal forest). To estimate changes in carbon storage, we calculated the Net Ecosystem Carbon Balance (NECB [see *Chapin et al.*, 2006]) for outputs generated by the model as:

$$NECB = NPP - R_h - TCE \quad (1)$$

where NPP is net primary production, R_h is heterotrophic respiration, and TCE is total carbon emitted due to fire. It is important to note that our analysis does not consider the effects of other disturbances that affect carbon storage in the pan-boreal region, for example, insect disturbance, forest harvest, or land-use change, in the calculation of NECB.

2.3. Input Data Sets

[10] To extrapolate TEM across North America and the pan-boreal region, we used driving data sets that had (1) temporal variability, but no spatial variability (atmospheric CO_2 concentration), (2) spatial variability but no temporal variability (elevation, soil texture, and vegetation), and both temporal and spatial variability (air temperature, precipitation, cloudiness, and fire disturbance). Below, we describe these data sets in more detail.

2.3.1. Atmospheric CO_2, Elevation, Soil Texture, and Vegetation Data Sets

[11] In this study, atmospheric CO_2 data were obtained from the Mauna Loa station [*Keeling and Whorf*, 2005]. TerrainBase v1.1 elevation data were obtained from the National Geophysical Data Center, Boulder, CO [*NGDC*, 1994] and aggregated to a 0.5° latitude × 0.5° longitude spatial resolution. Soil texture, represented as percent silt plus percent clay in TEM, was based on the Global Gridded Surfaces of Selected Soil Characteristics data set [*Global Soil Data Task Group*, 2000] and gridded at a 0.5° latitude × 0.5° longitude spatial resolution. The input vegetation data set, gridded at the 0.5° resolution, is represented by a potential natural vegetation map described by *Melillo et al.* [1993].

2.3.2. Temperature, Precipitation, and Cloudiness Data Sets

[12] Monthly air temperature (°C), precipitation (mm), and cloudiness (%) data derived from observations for the period 1901–2002 gridded at 0.5° resolution were obtained from the Climate Research Unit, University of East Anglia [*Mitchell and Jones*, 2005].

2.3.3. Historical Fire Data Sets

[13] A database of fire point location data and 1-km resolution fire scar data sets were acquired for Alaska, Canada, and Eurasia and then assembled into a 0.5° grid. For Alaska, we used the Alaska fire scar location database initially developed by *Kasischke et al.* [2002] and maintained by the *Bureau of Land Management* [2005]. The database contains point and boundary location information for fires in Alaska from 1950–2002. Fires greater than 1000 acres (~404 ha) are included from 1950–1987, inclusive, and fires greater than 100 acres (~40.4 ha) are included from 1988–2002, inclusive. Although our analysis is focused on the region north of 45°N, fires in the northern conterminous United States are not considered.

[14] For Canada we used a combination of point location data from the Canadian Large Fire Database (LFDB) and provincial polygon data, with a preference for using the provincial polygon data when available. The LFDB is a compilation of provincial and territorial wildfire data that represents all fires that are greater than 200 ha that occurred from 1959–1999. For the point location data sets for Canada [*Flannigan and Little*, 2002], we used the longitudinal and latitudinal point locations to calculate a radius for each location based on the area of the historical fire. Circular fire boundaries were then created for each point by buffering each point by a distance equal to the calculated radius. The provincial polygon data represent fires in all provinces from 1980–2002 (provided by M. Flannigan, Canadian Large Fire Database, 1980–2003 polygons, unpublished data, 2006). Also, historical fire data for Saskatchewan [*Naelapea and Nickeson*, 1998] and Alberta [*Government of Alberta*, 2005] were also available as polygon coverages for the periods 1945–1979 and 1931–1979, respectively. There was no redundancy between the use of point location data of the Canadian LFDB and the provincial polygon data in our assembly of the historical data set of fire in Canada for use in our simulations.

[15] For Russia, we used Advanced Very High Resolution Radiometer (AVHRR) satellite-derived fire scars data from 1996–2002 produced at the Sukachev Institute of Forestry in Krasnoyarsk [*Sukhinin et al.*, 2004].

[16] Our examination of the spatially explicit fire scar data indicated that there were a number of spatial units within each 0.5° grid cell that had unique fire histories over the length of the fire scar record. These unique fire histories result in stands of different age that have different legacies of fire disturbance on carbon storage within a 0.5° grid cell. To properly represent this legacy of disturbance within a 0.5° grid cell, we labeled each spatial unit within a 0.5° grid cell that has a unique fire history based on the fire scar record as a "cohort". The number of cohorts per grid cell depended on both the historical fire record and fires that we inserted prior to the start of the historical fire record as part of backcasting algorithm (see section 2.4). To estimate carbon storage changes for a 0.5° grid cell, we conducted simulations for each cohort within the grid cell and aggregated the simulated carbon storage estimates across all of the cohorts of the grid cell.

2.4. Fire Return Intervals and Backcasting

[17] To take into account fires prior to the start of the historical fire record, we developed a backcasting algorithm which requires information on the fire return interval (FRI). We defined FRI as the time required to burn an area equal to the entire 0.5° grid cell. Each cohort within a given 0.5° grid cell has the same FRI regardless of when the cohort burned historically. For North America, we calculated FRI based on the historical fire record from 1950–2002 in Alaska and 1959–2002 in Canada. This was accomplished by taking into account the proportion of a grid cell burned each year by first calculating a fire rate (F_R) given by:

$$FR = (A_B/A_T)/N_Y \quad (2)$$

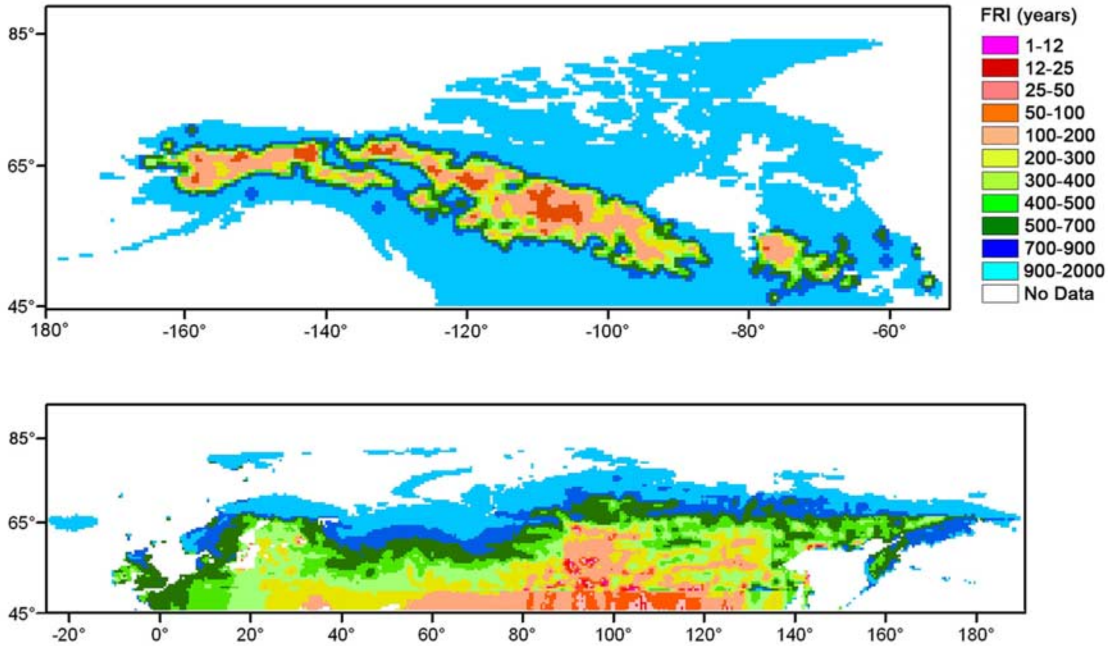

Figure 2. Fire return interval (FRI) maps for (a) North America and (b) Eurasia. North America FRIs were based on the proportion of a 0.5 degree cell burned over the historical fire record (1950–2002 for Alaska; 1959–2002 for Canada). Eurasian FRIs were interpolated using ordinary cokriging methods based on nontemporally explicit literature estimates.

in which A_B is the area burned within a 0.5° grid cell, A_T is the total area of the 0.5° grid cell, and N_Y is the number of years representing the historical fire record. Since FRI is the time required to burn an area equal to the entire 0.5° grid cell, it is calculated as the inverse of the fire rate:

$$\mathrm{FRI} = 1/\mathrm{F_R} \tag{3}$$

The FRI map as calculated above was then smoothed using a nearest-neighbor method in order to be more spatially representative of fire regime by reducing pixilation (Figure 2a).

[18] A different approach was used for estimating FRI for Eurasia (Figure 2b) because of the short length of the historical fire record as well as the lack of large-scale FRI data. FRIs were estimated based on available data using ordinary cokriging methods in the ESRI ArcMap v9.0 Geostatistical Analyst Extension Package. The available FRI data for Eurasia were obtained in the form of non-temporally explicit points provided by C. Wirth (unpublished data, 2006) and transects. Transect data are based on the IGBP high-latitude transect study of *McGuire et al.* [2002]. Vegetation data at 1-km resolution (E. S. Euskirchen et al., Energy feedbacks to the climate system associated with snow cover dynamics in northern high latitudes during warming periods of the 20th century, submitted to *Global Change Biology*, 2007) were used as a second predictor variable to help improve the interpolated surface. Because the fire scar record for boreal Eurasia is so short, we then adjusted the initial Eurasia FRI estimates based on the assumption that the ratio of mean annual area burned from 1996–2002 to long-term mean annual area burned was similar over the long-term in boreal Eurasia and Canada. To implement this assumption, the interpolated surface of the initial FRI (IFRI) estimates was standardized relative to a factor δ calculated from historical burn area for 1996–2002 and interpolated FRIs in Eurasia and Canada as:

$$\mathrm{FRI_{Eurasia}} = \delta\ \mathrm{IFRI_{Eurasia}} \tag{4}$$

in which δ is calculated as:

$$\delta = \varphi_E/\varphi_C \tag{5}$$

in which

$$\varphi_C = \mu_C/\mu_{\mathrm{FRICanada}} \tag{6}$$

and

$$\varphi_E = \mu_E/\mu_{\mathrm{IFRIEurasia}} \tag{7}$$

where φ_C and φ_E are the respective burn ratios for Canada or Eurasia, μ_C and μ_E are the respective mean annual areas burned from 1996–2002 for Canada and Eurasia, and $\mu_{\mathrm{FRICanada}}$ and $\mu_{\mathrm{IFRIEurasia}}$ are the respective mean annual areas burned based on interpolated fire return intervals for the boreal forest area of Canada and on the initial interpolated fire return intervals for the boreal forest area of Eurasia.

[19] Throughout the pan-boreal region, the interpolated FRIs were then used by the backcasting algorithm to insert fires prior to the start of the historical period based on the fire record of each cohort within a 0.5° grid cell and the FRI of that grid cell. Fires were inserted by one of two ways. If a given cohort burned over the length of the historical period,

Table 1. Literature Estimates of Average Aboveground (β_a) and Ground Layer (β_b) Carbon Fraction Consumed Used for Emissions Estimates During a Fire Event for North America [*French et al.*, 2000] and Eurasia [*FIRESCAN Science Team*, 1996; *Kajii et al.*, 2002; *Wirth et al.*, 2002a, 2002b][a]

Ecozone	Aboveground (β_a) C Fraction Consumed	Ground Layer (β_b) C Fraction Consumed	Average Area Burned, ha	Average Emission, Tg C yr^{-1}	Average Emission per m^2 of Burned Area, g C m^2 yr^{-1}
North America					
Alaska Boreal Interior	0.23	0.36	289000	7.2	2470
Boreal Cordillera	0.13	0.38	159000	5.7	3580
Taiga Plain	0.25	0.06	362000	6.0	1650
West Taiga Shield	0.25	0.05	369000	3.3	896
East Taiga Shield	0.25	0.05	141000	2.1	1490
West Boreal Shield	0.26	0.06	531000	15.2	2860
East Boreal Shield	0.22	0.06	95000	0.2	256
Boreal Plain	0.24	0.11	227000	7.8	3420
Hudson Plain	0.24	0.05	56300	0.8	1430
Eurasia					
Larch Forests	0.15	0.28	2090000	106.8	5110
Ground fire regime	0.15	0.15	2540000	73.3	2880
Grassland/Steppe	0.85	0.01	753000	35.6	4720

[a]Also shown are mean annual area burned, mean annual total carbon emission, and mean annual total carbon emission per square meter of burned area from model simulations for North America (1959–2002) and Eurasia (1996–2002).

previous fire(s) events were calculated by the difference between the first historical burn year and the FRI. If the cohort did not burn during the historical fire record, fires were inserted stochastically based on the FRI of the grid cell prior to the historical fire record. Backcasting fires only occurred if the grid cell FRI was less than or equal to 500 years (i.e., each cohort would burn at least two times during a 900 year spin-up period), allowing a dynamic equilibrium to be reached prior to the start of the realistic transient climate period (1901–2002). Fires were not inserted for Europe (defined as west of 22°E and north of 45°N in this study) because we assumed that human activities have effectively suppressed wildfire in this region; the historical fire record we used for Russia did not contain any fires west of 22°E and north of 45°N.

2.5. Burn Severity Implementation

[20] Our approach to modeling emissions is based on calculating the total carbon emitted during a fire event from aboveground and ground layer carbon consumption estimates. Literature estimates (Table 1) of aboveground and ground layer carbon fraction consumed during a fire for boreal North America [*French et al.*, 2000] and boreal Eurasia [*FIRESCAN Science Team*, 1996; *Kajii et al.*, 2002; *Wirth et al.*, 2002b] are used to address the issue of burn severity. Total annual carbon emissions are then calculated using these parameters by calculating fluxes for both vegetation and soil carbon pools during a fire by:

$$\mathrm{TCE} = (\beta_a * V_c) + (\beta_g * S_c) \tag{8}$$

where TCE is the total carbon emitted, β_a is the aboveground C fraction consumed, β_g is the ground layer carbon fraction consumed during a fire, V_c is vegetation carbon, and S_c is soil carbon. Based on *Harden et al.* [2004] and *Wirth et al.* [2002a], we assumed that 85% of soil and vegetation nitrogen was retained at the time of fire. The nitrogen lost from the ecosystem as a result of fire was reintroduced into the system annually in equal increments obtained by dividing the total net nitrogen lost to the atmosphere during the most recent fire event by FRI.

[21] We also differentiated between crown and surface fires in our simulations. For boreal North America we assumed a fire regime that was predominantly stand replacing and specified that one percent of live plant biomass would be available for regeneration following a fire. For Eurasia, we assumed a stand-replacing fire regime for larch forests across eastern Siberia and grassland/steppe at the southern boundary of our study region. Areas east of 22°E not dominated by larch forests or grassland were classified as being driven by a surface fire regime, and we assumed that 60% of aboveground vegetation remains following fire events [*Wirth*, 2005].

3. Results

[22] We first present our estimates of fire emissions across North America and the pan-boreal region. We then examine the relative importance of these fire emissions to other environmental factors in the carbon dynamics of terrestrial ecosystems in North America and the pan-boreal region. North America is highlighted because we had a longer period of historical fire data for this region (1959–2002) than for the entire pan-boreal region (1996–2002).

3.1. Fire Emissions

[23] Fire emissions calculated by TEM are presented as total carbon lost to the atmosphere at the time of a fire event. We calculated decadal averages to examine the long-term trends in simulated fire emissions for boreal North America. The results of our simulations indicate that the decadal average annual fire emissions for Alaska, Canada, and North America (Alaska and Canada combined) approximately doubled from the 1960s to the 1980s and that CO_2 fertilization had little effect on the estimated emissions (Figure 3a). Although a slight decrease in average fire emissions from the 1980s to 1990s was simulated for Canada (and boreal North America), simulated fire emissions for Alaska nearly doubled.

[24] In our pan-boreal simulations from 1996–2002, boreal Eurasia accounted for approximately 80% of estimated emissions and CO_2 fertilization had little effect on

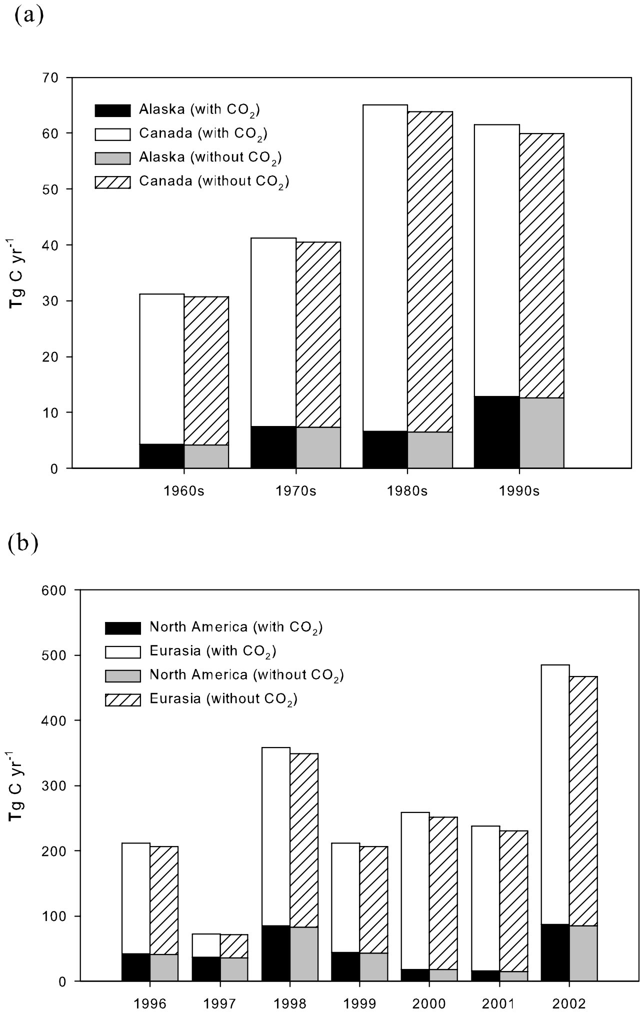

Figure 3. Fire emissions of total carbon: (a) average decadal emissions for Alaska and Canada; and (b) annual emissions for Eurasia and North America. Units are Tg C yr^{-1}.

emissions estimates. Across the pan-boreal region the estimated mean annual emissions of total carbon from 1996–2002 as a result of wildfire were 262.5 Tg C yr^{-1} and 254.5 Tg C yr^{-1} for the simulations that considered and excluded the effect of atmospheric CO_2 fertilization, respectively (Figure 3b). For Eurasia mean annual emissions of total carbon were 215.7 Tg C yr^{-1} and 208.8 Tg C yr^{-1} for the simulations that considered and excluded atmospheric CO_2 fertilization, respectively. The mean annual emissions of total carbon for the simulations that considered and excluded CO_2 fertilization for North America were 46.8 Tg C yr^{-1} and 45.7 Tg C yr^{-1}, respectively. For the North American sub-regions of Alaska and Canada, mean annual total carbon emissions for the simulation that considered CO_2 fertilization were estimated to be 13.9 Tg C yr^{-1} and 32.9 Tg C yr^{-1}, respectively, while the simulation that excluded CO_2 fertilization estimated emissions to be 13.7 Tg C yr^{-1} and 32.2 Tg C yr^{-1}.

[25] To understand the spatial variability of emissions among subregions with different burn severity parameters (Table 1), we calculated the mean annual area burned, mean total annual carbon emissions, and mean annual total carbon emissions per square meter of burned area for subregions of North America and Eurasia for the periods 1959–2002 and 1996–2002, respectively (Table 1). Across North America, the mean emissions per unit area burned was greatest across the Boreal Cordillera, Boreal Plain, West Boreal Shield, and the Alaska Boreal Interior subregions (Table 1). In our simulations, the three highest values for ground layer fraction consumed occur in the Boreal Cordillera, the Alaska Boreal Interior, and the Boreal Plain subregions, while the highest value of aboveground fraction consumed occurs in the West Boreal Shield (Table 1). Among the three subregions in Eurasia, the stand-replacing regime of the larch forest subregion, which has the highest value of ground layer fraction consumed in Eurasia (Table 1), was responsible for the highest carbon emissions per square meter of burned area (Table 1).

3.2. North American Carbon Dynamics 1959–2002

[26] Our simulations that considered atmospheric CO_2 fertilization estimate that boreal North America was a carbon sink of 81.7 Tg C yr^{-1} (7.5 g C m^{-2} yr^{-1}) from 1959–2002, while the simulations that excluded CO_2 fertilization estimate a sink of 18.7 Tg C yr^{-1} (1.5 g C m^{-2} yr^{-1}) over the same period (Table 2). For the case of CO_2 fertilization, climate variability and CO_2 fertilization were about equally responsible for sequestering carbon at a rate of 46.9 Tg C yr^{-1} (3.7 g C m^{-2} yr^{-1}) and 50.4 Tg C yr^{-1} (4.0 g C m^{-2} yr^{-1}), respectively, whereas fire was responsible for carbon release to the atmosphere at a rate of 15.6 Tg C yr^{-1} (1.2 g C m^{-2} yr^{-1}). The effect of CO_2 on carbon storage (Figure 4a) is generally positive across North America while the effect of climate on carbon storage shows both uptake from and release to the atmosphere (Figure 4b); release of carbon is most evident in the Canadian Archipelago, with greater release of carbon from the simulations that excluded CO_2 fertilization. In regions where fires are concentrated over the period 1959–2002 (interior Alaska extending southeast from the Yukon Territory through central Canada to portions of eastern Quebec), carbon losses are observed in response to fire, with greater losses observed for the simulations that excluded CO_2 fertilization, while areas not burned during this period generally responded as a carbon sink (Figure 4c). Overall, North America acts as a carbon sink in response to the combined effects of CO_2, climate, and fire (Figure 4d), except for regions where fires occurred and in the Canadian Archipelago which lost carbon in response to climatic variability.

[27] We further analyzed the effects of CO_2, climate, and fire for North America in order to understand how each effect influences decadal-scale carbon dynamics (Figure 5). Our analysis indicates that increasing CO_2 concentrations enhanced carbon storage per decade from the 1960s through the 1990s (Figure 5a). Similarly, carbon storage increased in response to increasing mean annual air temperature from the 1960s to the 1990s for both sets of simulations (Figure 5b). The effect of fire on carbon storage shows that the 1960s and 1970s were periods of sink activity, but that the sink weakened in the 1970s as area burned increased (Figure 5c). In the 1980s and 1990s, the effect of fire acted to release carbon to the atmosphere, with the effect being larger in the 1990s even though fire emissions were higher in the 1980s

Table 2. Mean Annual Changes in Carbon Storage Simulated for North America From 1959 to 2002 and for the Pan-Boreal Region From 1996 to 2002[a]

		Effects			
Period	Region	CO_2	Climate	Fire	Total
		With CO_2 Fertilization			
1959–2002	North America	50.4	46.9	−15.6	81.7
1996–2002	Pan-boreal	284.6	136.9	−15.9	405.6
	Eurasia	207.7	50.9	21.5	280.2
	North America	76.9	86.0	−37.5	125.4
		Without CO_2 Fertilization			
1959–2002	North America	−0.3	36.4	−17.4	18.7
1996–2002	Pan-boreal	−0.2	36.9	−41.6	−4.9
	Eurasia	0.1	−29.4	−0.1	−29.4
	North America	−0.3	66.3	−41.5	24.5

[a]Units are given in Tg C yr^{-1}. Positive values represent carbon sequestered by terrestrial ecosystems, while negative values represent release of carbon.

(Figure 3a). It is important to recognize that the effect of fire during a particular decade in Figure 5c is not simply correlated with fire emissions as it integrates the legacy of how fire history influences the balance between NPP and R_h on regrowing stands during the decade in addition to fire emissions during the decade. Thus, from the 1970s through the 1990s, our simulations indicate that the increase in mean annual area burned promoted decreases in carbon storage. The combined effects of CO_2, climate, and fire in our simulations indicate, however, that North America acted as a carbon sink in each decade from the 1960s to 1990s (Figure 5d). The simulated sink activity generally increased over time with a slight dip in the 1980s and was greatest in the 1990s. The combined effects of climate and fire for the simulations that excluded CO_2 fertilization show sink activity from the 1970s through 1990s, with an increase in sink activity from the 1960s to 1970s followed by a decrease from the 1970s to the 1980s and 1990s due to an increase in the area burned between the two decades.

3.3. Pan-Boreal Carbon Dynamics for 1996–2002

[28] For the period from 1996 through 2002, we estimate that carbon storage of the pan-boreal region north of 45°N increased by 405.6 Tg C yr^{-1} (10.6 g C m^{-2} yr^{-1}) in response to CO_2, climate, and fire (Table 2). We estimate that about twice as much carbon has been sequestered in Eurasia than in North America. For the pan-boreal region, our simulations that considered CO_2 fertilization indicate that CO_2 fertilization sequestered over twice as much carbon (284.6 Tg C yr^{-1} or 7.5 g C m^{-2} yr^{-1}) as climate variability (136.9 Tg C yr^{-1} or 3.6 g C m^{-2} yr^{-1}), and that fire was responsible for releasing 15.9 Tg C yr^{-1} (0.4 g C m^{-2} yr^{-1}) to the atmosphere. For both North America and Eurasia, the simulated effects of atmospheric CO_2 and climate variation were responsible for sequestering carbon while fire acted to release carbon to the atmosphere. Similar to our longer-term analysis for boreal

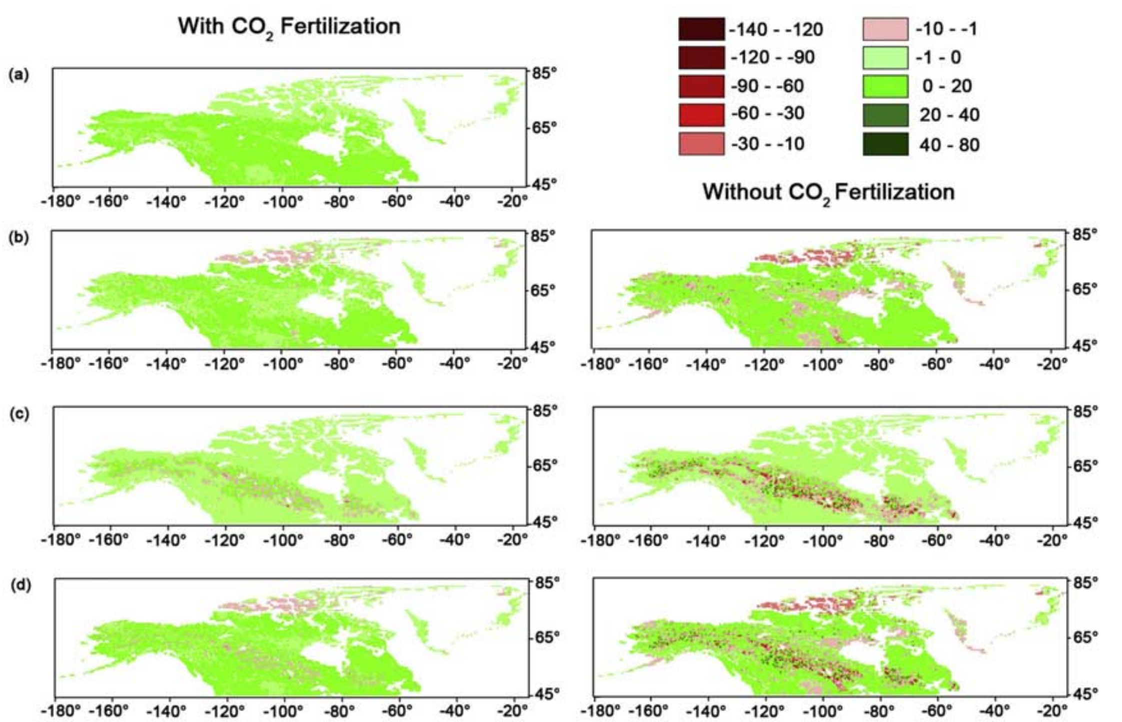

Figure 4. Simulated mean annual net ecosystem carbon balance (NECB) of North America from 1959–2002 in response to (a) CO_2 fertilization, (b) climate, (c) fire, and (d) CO_2, climate, and fire. Results are presented for simulations conducted with and without a CO_2 fertilization effect on photosynthesis. A control corresponding to Figure 4a for the simulations without CO_2 fertilization is not presented because NECB would be zero throughout the region. Units are in g C m^{-2} yr^{-1}. Positive values represent carbon sequestered by terrestrial ecosystems, while negative values represent release of carbon to the atmosphere.

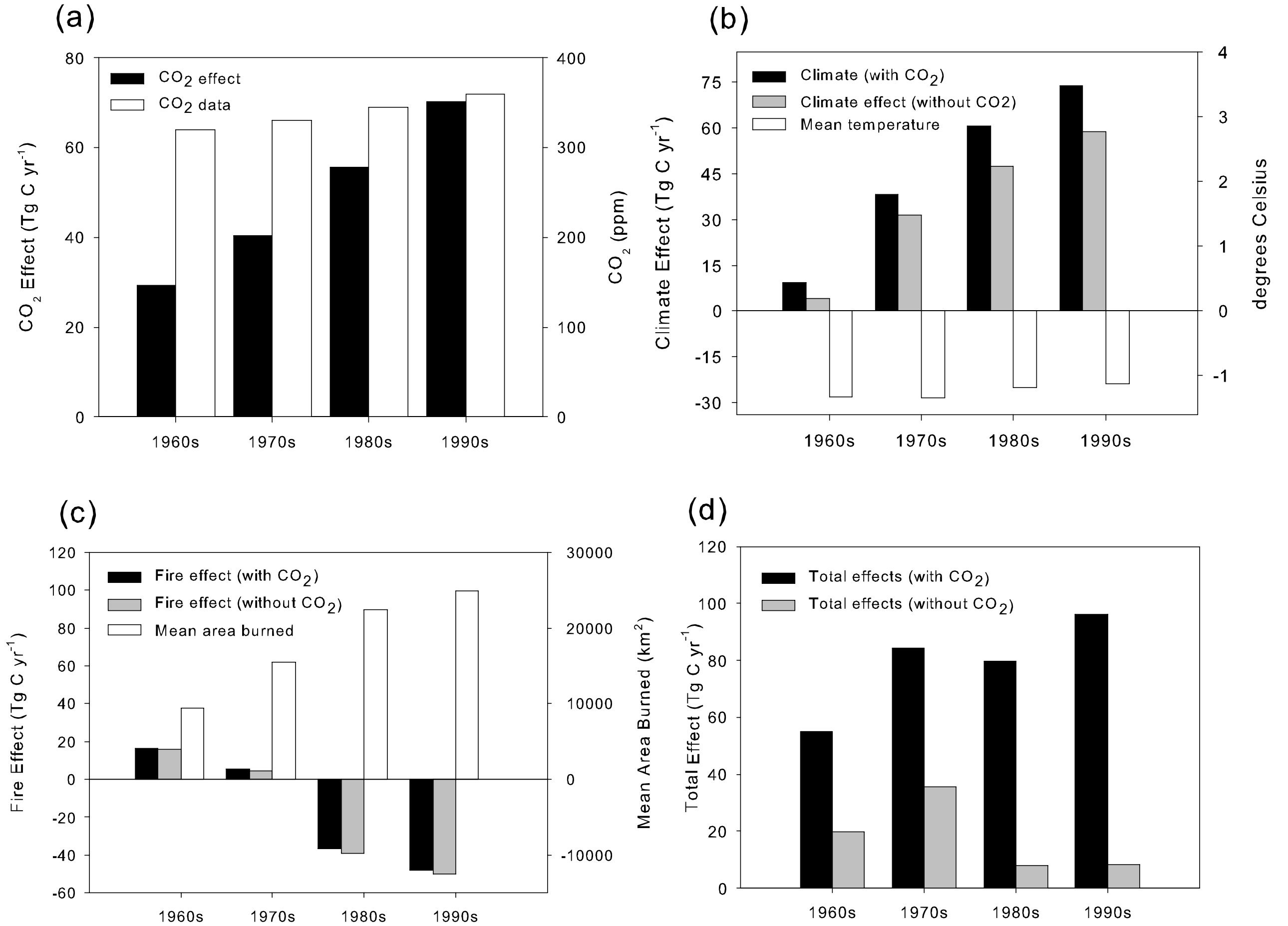

Figure 5. Decadal effects of (a) CO_2, (b) climate, (c) fire, and (d) the combination of CO_2, climate and fire on simulated net ecosystem carbon balance for North America from the 1960s through the 1990s. Effects are compared to model driving data of mean decadal CO_2, air temperature, and area burned. Positive values represent carbon sequestered by terrestrial ecosystems, while negative values represent release of carbon to the atmosphere.

North America, the effects of CO_2 and climate are similar in promoting carbon storage in boreal North America from 1996–2002. In contrast, the effects of increasing CO_2 are about four times larger than the effects of climate in promoting carbon storage in Eurasia. Our simulations indicate that the effects of fire in North America are about four times larger than in Eurasia in promoting carbon release between 1996 and 2002.

[29] The simulations that excluded CO_2 fertilization estimate that the combined effects of climate and fire were responsible for a release of 4.9 Tg C yr^{-1} (0.1 g C m^{-2} yr^{-1}) to the atmosphere over the period 1996–2002 (Table 2). Of these effects, climate was responsible for sequestering 36.9 Tg C yr^{-1} (1.0 g C m^{-2} yr^{-1}) while fire was responsible for releasing 41.6 Tg C yr^{-1} (1.1 g C m^{-2} yr^{-1}) to the atmosphere.

[30] To better understand how CO_2 fertilization, climate and fire may have influenced carbon storage in the pan-boreal region, we first analyzed the patterns of interannual variability in terrestrial carbon storage or loss. Increasing atmospheric CO_2 concentration increased carbon storage from 1996–2002 (Figure 6a). Our analysis of the effect of climate on carbon storage did not identify a relationship with mean annual air temperature from 1996–2002 (Figure 6b). In comparison to the simulations that considered CO_2 fertilization, the effect of climate on carbon storage in the simulations that excluded CO_2 fertilization was to generally act as either a smaller sink or a greater source (Figure 6b). We evaluated relationships between the climate effect on carbon storage and associated air temperature and precipitation for each subregion (boreal Eurasia and North America) and for each vegetation type within a subregion, but at these scales we could not explain how climate variability influenced interannual variation in carbon storage with simple empirical relationships. The effect of fire on carbon storage shows that as total area burned increases, carbon storage decreases (Figure 6c). For both sets of simulations, larger fire years promoted less carbon storage than more moderate fire years. Overall, our simulations of the combined effects of CO_2, climate, and fire indicate that the pan-boreal region acted as a carbon sink from 1996–2002 except for an estimated release of carbon in 2002 (Figure 6d). In contrast, the combined effects of climate and fire for simulations excluding CO_2 indicate that the pan-boreal region acts as a carbon source in larger fire years.

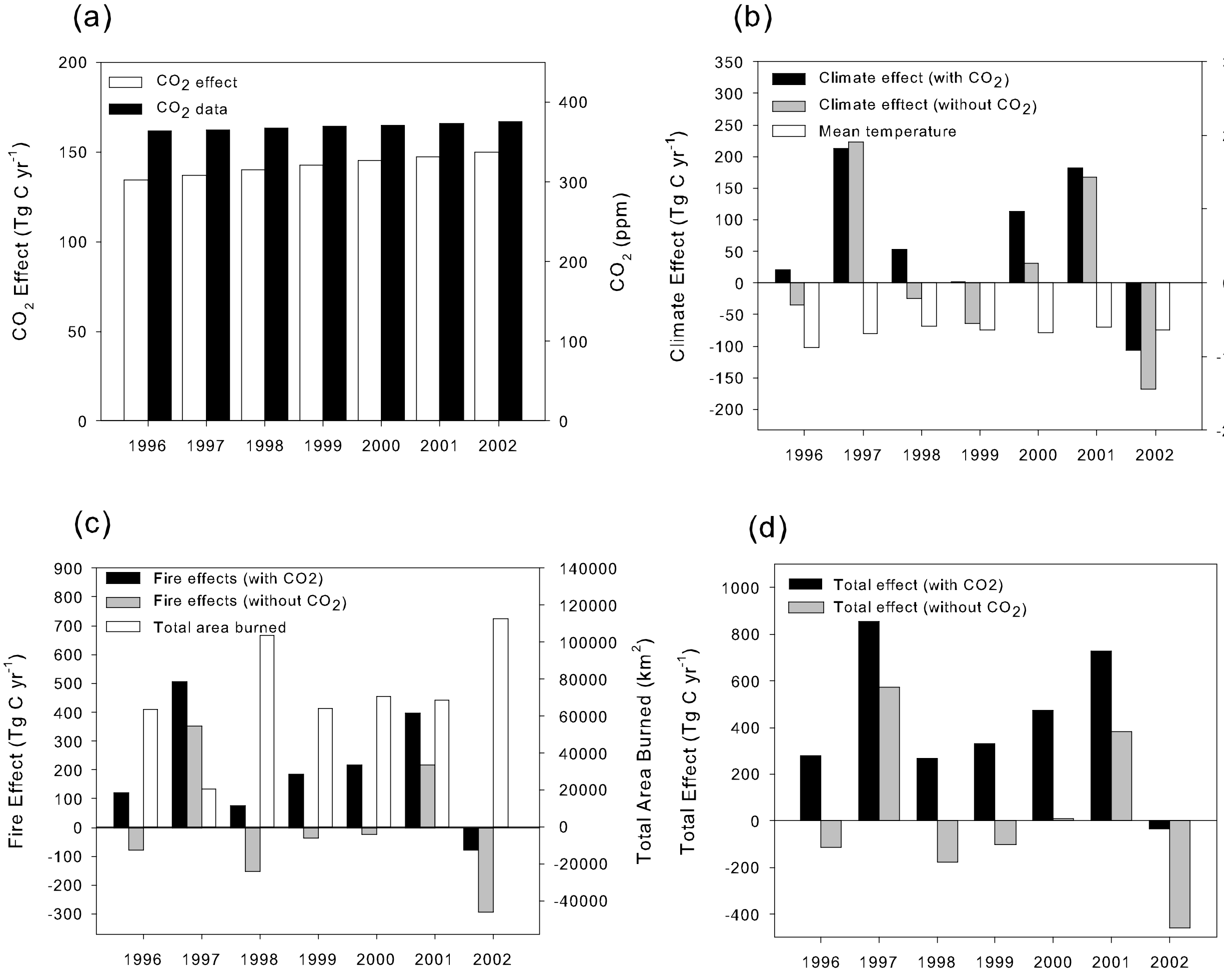

Figure 6. Effects of (a) CO_2, (b) climate, (c) fire, and (d) the combination of CO_2, climate and fire on simulated annual net ecosystem carbon balance for the pan-boreal region from 1996–2002. Effects are compared to model driving variables of annual CO_2, air temperature, and total area burned. Positive values represent carbon sequestered by terrestrial ecosystems, while negative values represent release of carbon to the atmosphere.

[31] We further explored how the influence of these environmental factors on carbon storage varied spatially (Figure 7). Across the pan-boreal region increasing atmospheric CO_2 promoted carbon storage (Figure 7a), while climate variability promoted both source and sink activity (Figure 7b). Across Eurasia, losses associated with climate are observed south of the Scandinavian region, the Kazakh Uplands, and the Mongolian Plateau, while in North America losses are observed in the Queen Elizabeth Islands and portions of Alberta and Saskatchewan. In Eurasia, carbon losses appear to be greater south of the Scandinavian region for the simulations without CO_2 fertilization. Carbon gains associated with climate occur across Eurasia from western Europe to the Russian Far East and across North America from Alaska to Labrador. The effect of fire generally promoted losses of carbon to the atmosphere in areas that were identified as burned in the historical fire records that we used to drive our simulations (Figure 7c). The combined effects of CO_2, climate, and fire generally promoted carbon storage across the pan-boreal region except for carbon losses in areas where fire occurred between 1996 and 2002 (Figure 7d). The combined effects of climate and fire also show a similar pattern for the simulations without CO_2 fertilization; however, regions across Eurasia (south of the Scandinavian region to the Russian Far East) and North America (Canadian Archipelago) show greater carbon losses.

4. Discussion

[32] The results presented here attempt to evaluate the historical effects of fire disturbance on carbon dynamics across the entire pan-boreal region in the context of changes in atmospheric CO_2 and climate. We also discuss uncertainties with respect to the role of atmospheric CO_2 fertilization in calculating the overall carbon budget. Given the spatial and temporal scales of our analysis, it is difficult to conduct a direct validation of our results. We are able, however, to compare our results with the existing regional estimates of fire emissions and carbon balance to evaluate interannual and decadal variation in our simulations.

4.1. Comparison of Fire Emission Estimates

[33] Our estimates of fire emissions reported for each set of simulations do not appear to be greatly influenced by our

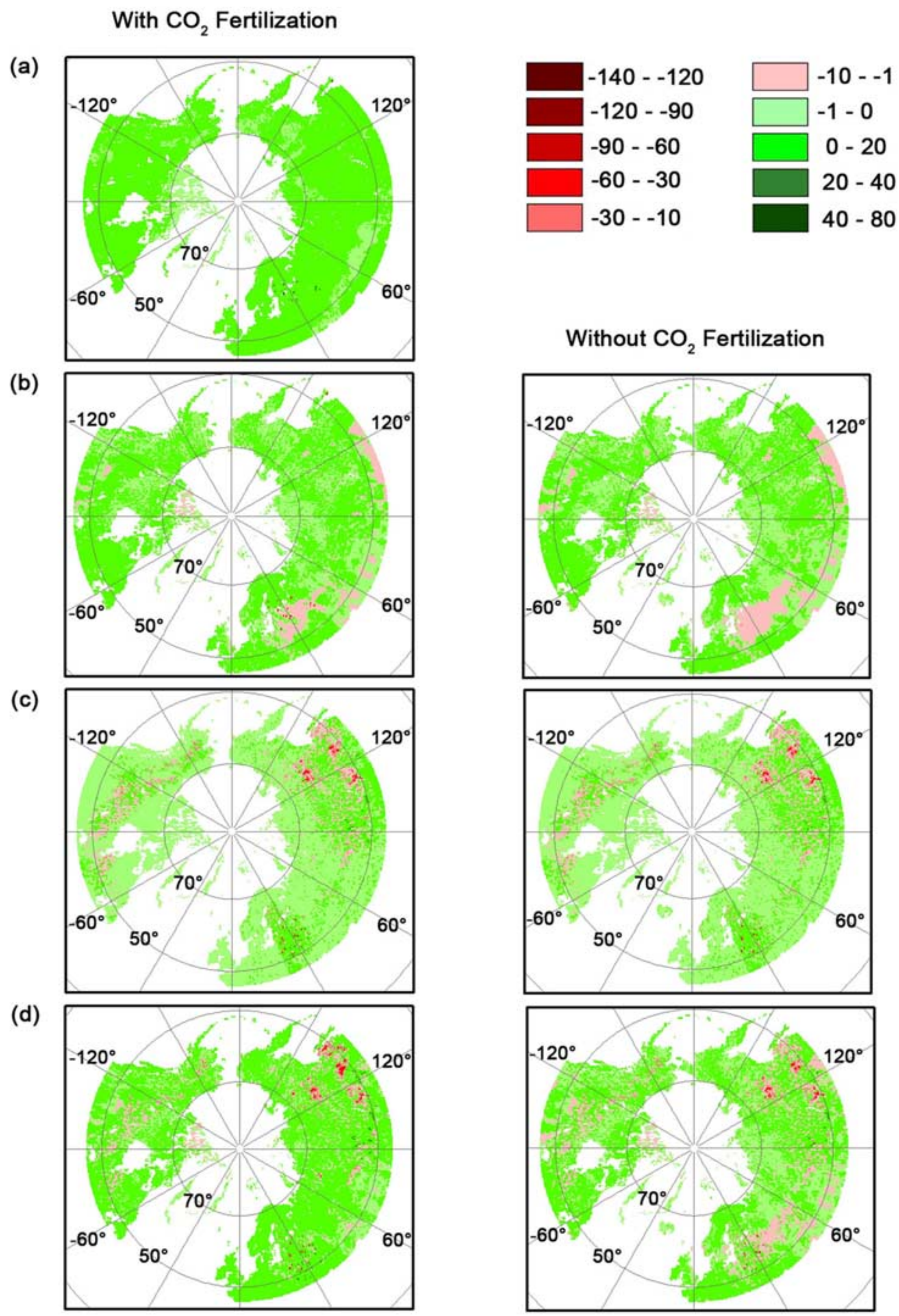

Figure 7. Simulated mean net ecosystem carbon balance (NECB) of the pan-boreal region from 1996–2002 in response to (a) CO_2 fertilization, (b) climate, (c) fire, and (d) the combination of CO_2, climate, and fire. Results are presented for simulations conducted with and without a CO_2 fertilization effect on photosynthesis. A control corresponding to Figure 7a for the simulations without CO_2 fertilization is not presented because NECB would be zero throughout the region. Units are in g C m^{-2} yr^{-1}. Positive values represent carbon sequestered by terrestrial ecosystems, while negative values represent release of carbon to the atmosphere.

implementation of the effects of CO_2 fertilization on photosynthesis. The simulations that considered atmospheric CO_2 fertilization are between 1–14 Tg C higher than those that excluded the effect of CO_2 fertilization. A number of studies have been conducted that use long-term historical fire data sets to estimate fire emissions within our study region (Table 3). For boreal North America, our estimates are 15–31% higher than the decadal scale estimates of *Conard and Ivanova* [1997] and *French et al.* [2000]. It is important to recognize that the burn severity parameters for

Table 3. Comparison of Emissions Estimates (Total Carbon Emitted, Tg C yr^{-1}) From Previous Studies With Estimates Developed in This Study

Region	Study	Years	Emissions	This Study	
				With CO_2	Without CO_2
Canada	*Amiro et al.* [2001]	1959–1995	26	41	40
	Mouillot et al. [2006]	1990–1999	43	49	47
Boreal North America	*Conard and Ivanova* [1997]	1971–1991 mean	42	55	53
	French et al. [2000]	1980–1994 mean	53	61	60
	Conard et al. [2002]	1998	52–55	85	83
	van der Werf et al. [2006]	1997–2002 mean	35	48	46
Pan-boreal	*Conard et al.* [2002]	1998	187–245	358	349
	Kasischke and Bruhwiler [2002]	1998	290–383	358	349
	Kasischke et al. [2005]	Range of mean emissions for 1996–2002[a]	110–211	262	255
	Yurganov et al. [2004]	1996–2001 mean	6–63	225	219
	Zhuang et al. [2006]	1990–1999 mean	58	256	245
	Mouillot et al. [2006]	1990–1999 mean	209	256	245
Boreal Russia/Siberia	*Conard and Ivanova* [1997]	1971–1991 mean	194	204	197
	Conard et al. [2002]	1998	135–190	273	266
	Shvidenko and Nilsson [2000]	1988–1992 mean	58	244	230
	Kajii et al. [2002]	1998	176	273	266
	Soja et al. [2004]	1998–2002 mean	116–520	261	252
	van der Werf et al. [2006]	1997–2002 mean	185	223	216
	Mouillot et al. [2006]	1990–1999 mean	166	194	185

[a]Range is based on average emissions from low and high burn severity scenarios for this period.

boreal North America in our simulations are based on burn severity parameters from *French et al.* [2000]. *Amiro et al.* [2001] used the Canadian Forest Fire Behaviour Prediction System (FBP) System model [*Forestry Canada*, 1992] to estimate both the surface and crown fuel consumed during a fire, and used these estimates to calculate carbon emissions for Canada. Although interannual variability in our emissions between 1959 and 1995 are highly correlated with those of Amiro et al. from 1959–1995 (Figure 8; R^2 = 0.92), they are higher by about 50%. The discrepancy between our estimates and *Amiro et al.* [2001] appears to be associated with the higher level of soil organic matter consumed associated with our use of the *French et al.* [2000] carbon consumption estimates [see also *Kasischke and Bruhwiler*, 2002].

[34] Across the pan-boreal region from 1996–2002, our estimates of emissions are higher than the range of emissions estimated by *Yurganov et al.* [2004], *Kasischke et al.* [2005], *Mouillot et al.* [2006], and *Zhuang et al.* [2006] (Table 3). Note that the range of emissions estimated by *Kasischke et al.* [2005] does not overlap with the range of *Yurganov et al.* [2004]. Our estimates of fire emissions for boreal Russia (Table 3) are also higher than those of *Conard and Ivanova* [1997] for 1971–1991 and those of *Shvidenko*

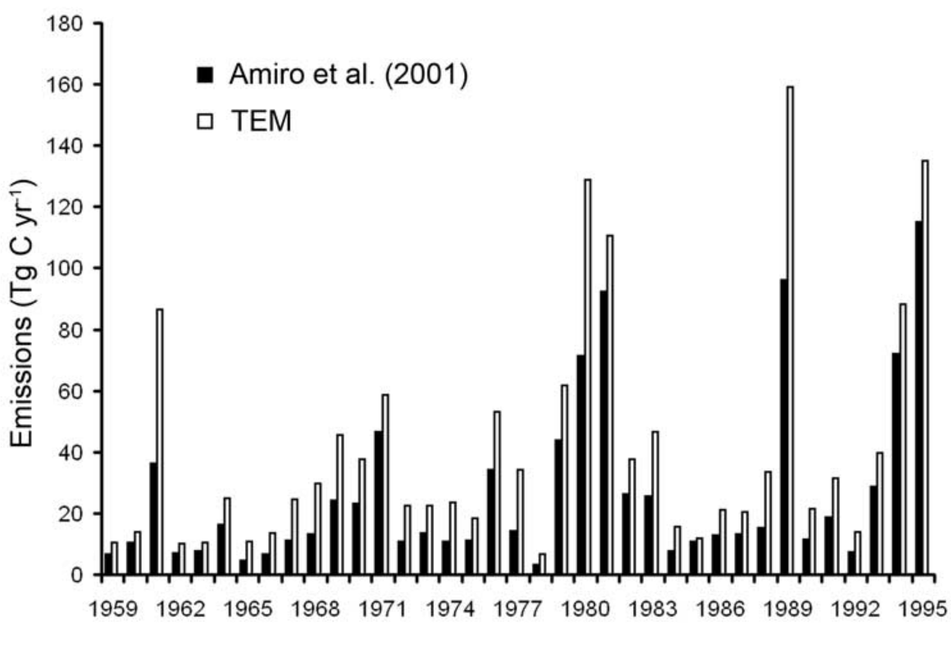

Figure 8. Comparison of TEM emission estimates for Canada with estimates from *Amiro et al.* [2001].

Table 4. Comparison of Previous Carbon Balance Estimates (Tg C yr^{-1}) With Estimates From This Study

Study Type	Years	Region	Literature Estimates	This Study	
				With CO_2	Without CO_2
Atmospheric inversion					
Gurney et al. [2004]	1992–1996	Boreal North America	−200 ± 280	91	12
		Boreal Asia	360 ± 510	227	−52
Inventory-based					
Shvidenko and Nilsson [2002][a]	1961–1998 mean	Russia	210 ± 30	159	70
Shvidenko and Nilsson [2003][b]	1961–1998 mean	Russia	322	220	68
Myneni et al. [2001]	1995–1999 mean	Canada	73	80	0.4
		Eurasia	470	314	−4
Kurz and Apps [1999][c]	1970–1989 mean	Canada	52	58	12
Process-based					
Chen et al. [2000][c]	1980–1996	Canada	53 ± 27	57	−1

[a]Average net carbon storage in vegetation only.
[b]Average net carbon storage in vegetation and soil while also taking into account fluxes generated by disturbances.
[c]Results include disturbances due to fire, insects, and logging.

and Nilsson [2000] for 1988–1992, which are time periods that correspond to the backcasting portion of our simulations for Eurasia. Our estimates are also higher than those estimated by *van der Werf et al.* [2006] for the period 1997–2000 and by *Mouillot et al.* [2006] for the 1990s. In contrast, our estimate of fire emissions for boreal Siberia from 1998–2002 are within the range reported by *Soja et al.* [2004, Table 3], but it should be noted that the range is quite large.

[35] Because 1998 was a high fire year in Eurasia, a number of studies have conducted analyses of fire emissions for that year. Our estimate of 1998 emissions at the pan-boreal scale (Table 3) is within the range reported by *Kasischke and Bruhwiler* [2002], but is substantially higher than the range reported by *Conard et al.* [2002]. Similarly, our estimates at the boreal Russia/Siberia scale (Table 3) are substantially higher than *Conard et al.* [2002] and *Kajii et al.* [2002].

[36] The comparison of fire emissions between our study and those of other studies identify that there is substantial uncertainty in estimates of fire emissions in the pan-boreal region. Our estimates of fire emissions tend to be higher than many of the previously published estimates because of the burn severity parameters that we used in this study. Thus, the uncertainty among studies appears to be largely associated with how burn severity is implemented among the approaches, an issue which we discuss in more detail below.

4.2. Comparison of Carbon Balance Estimates

[37] Inverse modeling studies have estimated exchange of CO_2 between the pan-boreal region and the atmosphere based on variability in the concentration of CO_2 that has been measured at various sites throughout the globe [e.g., *Dargaville et al.*, 2006]. The results of our simulations for the combined responses to changes in atmospheric CO_2, climate, and fire are within the range of uncertainty reported by *Gurney et al.* [2004] for boreal Asia and boreal North America from 1992–1996 (Table 4). However, it is important to note that the range of uncertainty from inversion-based modeling studies is quite large. We further compare our results to inventory- and process-based modeling studies to gain additional insight. In interpreting these comparisons it is also important to recognize that our simulations only considered one disturbance factor (fire), and that other disturbance factors in the pan-boreal region (e.g., insect disturbance, forest harvest, and land-use change) have the potential to influence regional carbon dynamics. For example, the analysis of *Kurz and Apps* [1999] indicates that insect disturbance was responsible for more loss of carbon than fire from Canadian forests in the late twentieth century.

[38] Inventory-based modeling studies capture a wide range of impacts on carbon dynamics from human to natural disturbance. These studies generally focus on particular transects or regions in the boreal forest, and are useful because they incorporate natural and anthropogenic disturbance regimes. In contrast, the estimates from our simulation consider the influence of fire disturbance in addition to CO_2 fertilization and climate variability. In comparison to previous inventory studies for Russia, the increase in vegetation carbon storage estimated by our simulations are substantially lower than the increases estimated by *Shvidenko and Nilsson* [2002, 2003], which considered a broader array of disturbances (Table 4). *Myneni et al.* [2001] conducted a study that relied on regression relationships between satellite-derived reflectance and forest inventory information to estimate changes in carbon storage for terrestrial areas north of 30°N from 1995–1999. In comparison to estimates of *Myneni et al.* [2001], the estimates of changes in carbon storage from our simulations that incorporated atmospheric CO_2 fertilization are slightly higher for Canada and substantially lower for Eurasia. *Kurz and Apps* [1999] conducted an inventory-based modeling study across Canada that analyzed variability across multiple decades. Over the period 1970–1989, they report a change in carbon storage that is similar to the estimate from our simulations that incorporate atmospheric CO_2 fertilization (Table 4). They also reported that Canadian forests acted as a sink from 1920–1979, and then changed to a source from 1980–1989 as a result of changes to the disturbance regime as the area affected by insect outbreaks and fires increased in the 1970s. Our results are consistent with these conclusions, but it is likely that our estimates of carbon storage in Canada in the late twentieth century would be lower if we considered insect disturbance in addition to fire. However, carbon storage in our simulations would likely be higher if we considered the effects of nitrogen deposition in fertilizing ecosystems in eastern Canada. In general, the simulations we conducted that considered an atmospheric CO_2 fertilization effect appear to be more consistent with estimates of

changes in carbon estimated by inventory-based modeling studies than the simulations that excluded CO_2 fertilization. Thus, our study suggests that ecosystem responses to changes in atmospheric CO_2 may be important to consider in addition to changes in climate and disturbance regimes.

[39] The influence of fire has been incorporated into several process-based models and studies have focused primarily on either modeling the regional or global area burned [*Venevsky et al.*, 2002; *Thonicke et al.*, 2001] or investigated carbon fluxes in response to fire for specific regions [*Chen et al.*, 2000, 2003; *Hicke et al.*, 2003; *Amiro et al.*, 2000; *Peng and Apps*, 1999]. While several process-based models have been applied at large spatial scales [*Potter et al.*, 2005, 2003b; *McGuire et al.*, 2001], they do not coincide well with our study region or have not explicitly considered the effects of historical fire. *Zhuang et al.* [2006] simulated the effects of fire on carbon dynamics for high-latitude ecosystems north of 50°N from 1860–2100 and reported an overall net CO_2 source of 240 Tg C yr^{-1} for the 1990s. The approach of *Zhuang et al.* [2006] differed from the approach of this study in several ways, but the key methodological difference responsible for the differences in results of the two studies is the assumption by *Zhuang et al.* [2006] of a fixed fire return interval (150 years) throughout the region to account for fires prior to the start of the historical record. This highlights the sensitivity of simulated carbon dynamics to factors affecting the stand age distribution of forests in the simulations. Another process-based modeling study that has considered historical fire is *Chen et al.* [2000], which used the Integrated Terrestrial Ecosystem Carbon-budget model (InTEC) to simulate the annual carbon balance of Canada's forests from 1896–1996 in response to CO_2, climate, nitrogen deposition, and disturbance (insects, logging, and fire). The analysis of *Chen et al.* [2000], which considered Canada as being one spatial unit, estimated that Canada was a sink for carbon from 1980–1996. Our simulations driven by changes in CO_2, climate, and fire are within the range of variability reported by *Chen et al.* [2000] but are substantially lower for the simulations that excluded the effect of atmospheric CO_2 fertilization (Table 4). While our analysis is not exactly comparable to *Chen et al.* [2000] as it did not consider the effects of forest harvest, insect disturbance, or nitrogen deposition, both studies highlight the potential importance of responses of ecosystems to variability in atmospheric CO_2 and climate in addition to changes in disturbance regimes.

4.3. Relative Roles of CO_2, Climate, and Fire

[40] The advantage of using process-based models for simulating carbon dynamics is that individual processes that affect carbon storage can be isolated. This helps to provide a better picture of the roles of different environmental factors on carbon storage that cannot be addressed through atmospheric inversion and inventory-based modeling studies. Our analysis identifies that CO_2, climate, and fire each have substantial influences on simulated carbon dynamics across the pan-boreal region. For the factors included in this analysis, if we group the effects into nondisturbance factors (CO_2 fertilization and climate variability) and disturbance factors (fire), our analysis indicates that the nondisturbance factors are primarily responsible for the estimated carbon sink for the period 1996–2002. A similar conclusion was found across Canada for the 1980s and 1990s, which is also consistent with other findings for that region [*Chen et al.*, 2003]. As stated earlier, it is important to recognize that our simulations do not incorporate other disturbance factors including insect disturbance, forest harvest, and land-use change.

[41] Although the response of TEM to increases in atmospheric CO_2 is highly constrained by the representation of the nitrogen cycle in the model [*McGuire et al.*, 1993, 1997, 2001; *Kicklighter et al.*, 1999], the model does have the capacity for a response to increasing atmospheric CO_2 as the ratio of vegetation carbon to nitrogen widens [*McGuire et al.*, 1997]. For the pan-boreal region from 1996–2002, the CO_2 fertilization effect in our simulations is 7.5 g C m^{-2} yr^{-1}. There is still substantial debate about whether or not CO_2 fertilization is occurring in the terrestrial biosphere [*Caspersen et al.*, 2000; *Hungate et al.*, 2003; *Luo et al.*, 2004; *DeLucia et al.*, 2005; *Norby et al.*, 2005], and the resolution of this issue remains an important challenge as many process-based models indicate that this factor is responsible for substantial sink activity in the terrestrial biosphere in recent decades [e.g., *McGuire et al.*, 2001]. The comparison of our simulations that both incorporate and exclude atmospheric CO_2 fertilization highlight this uncertainty. In general, the results of our simulations that incorporate an atmospheric CO_2 fertilization effect appear to be more consistent with previous analyses of carbon dynamics in the pan-boreal region.

[42] The positive response of carbon storage to warming climate in our simulations is largely associated with the increase of soil nitrogen availability to vegetation as increased decomposition in response to soil warming enhances nitrogen mineralization. This response of TEM is well-documented [e.g., *McGuire et al.*, 1992; *Melillo et al.*, 1993; *Xiao et al.*, 1997; *Tian et al.*, 1999], but there is much interannual and spatial variability in the response as it depends on soil moisture status [*McGuire et al.*, 2000a; *Thompson et al.*, 2006]. Over decadal timescales the response to a warming climate in the simulation results reported in this study was in general characterized by a faster increase in net primary production (NPP) than in decomposition, a pattern that resulted in a carbon sink of 3.6 g C m^{-2} yr^{-1} associated with climate variability between 1996 and 2002 at the pan-boreal scale. The increase in NPP in our simulations is consistent with a number of studies that have suggested that NPP in the pan-boreal region has been increasing in recent decades in response to warming [*Nemani et al.*, 2003; *Euskirchen et al.* 2006; *Kimball et al.*, 2006, 2007; see *Goetz et al.*, 2005]. Our study is also consistent with a recent study indicating that boreal ecosystems sequester more carbon in warmer years [*Chen et al.*, 2006].

[43] Although the effects of nondisturbance factors generally outweigh the effects of fire, we show that it is important to incorporate the role of fire when calculating the overall carbon budget for the pan-boreal region. Incorporating fire in our analysis shows that it reduces carbon storage across the pan-boreal region and, in large fire years (or averaged over decades), can switch from acting as a carbon sink to a carbon source to the atmosphere. Thus, fire plays an important role in the interannual variation in

source/sink relationships. Although we find that the effects of fire are less than the effects of CO_2 and climate, increases in fire frequency and burn severity in a changing climate may enhance the effect of fire on carbon dynamics across the pan-boreal region.

4.4. Limitations, Uncertainties, and Future Challenges

[44] We encountered several issues when attempting to evaluate the role of historical fire on high latitude carbon dynamics. We identify four main challenges that are important in influencing fire emissions estimates as well as the overall carbon budget: (1) the length of historical fire records, (2) the methods used for calculating stand age distribution prior to the start of the historical record, (3) accurately representing the influence of burn severity on carbon and nitrogen consumption, and (4) the role of peatland fires in estimating fire emissions.

[45] The lack of long-term spatially explicit fire data for Eurasia continues to be a problem for attempting to evaluate the role of fire in carbon dynamics of this region. This limitation also creates a great challenge with respect to accurately representing the state of the fire-driven landscape through the insertion of fires prior to the short historical record using coarsely interpolated fire return intervals. Our results presented here rely on a seven year historical period in terms of inserting pre-historical fires and therefore the frequency and size of fires in the short period is most likely not representative of the long term dynamic of fires that occur across Eurasia. Extending the existing satellite derived fire record prior to 1996 would help to reduce uncertainties. The extensive historical fire record for North America gives us a better understanding of the role of fire on carbon dynamics over the longer term and can be used to help reduce uncertainties that are associated with the short record for Eurasia for interpolating fire return intervals (e.g., standardizing Eurasian FRIs relative to North American FRIs).

[46] Another challenge that is closely related to the issue of data limitation on historical fires is the need to accurately represent the age distribution of forests prior to the start of using historical fire records in simulations. *McGuire et al.* [2004] documented that assumptions about historical fire prior to the start of the historical record have a large effect on simulations of carbon storage in Alaska. In boreal North America, we relied on using FRI based on the fire records from 1950–2002 in Alaska and 1959–2002 in Canada. The implementation of this approach essentially makes the assumption that the fire effect is neutral over these time periods in Alaska and Canada. However, our simulations estimated a fire effect of 15.6 to 17.4 Tg C, depending on CO_2 fertilization (Table 2), from terrestrial ecosystems of boreal North America to the atmosphere. Thus, the fire effect we report for boreal North America in this study may largely be an artifact of how fires were inserted prior to the start of the historical record. For Eurasia we relied on using FRI from sparse literature estimates, which may result in estimates of FRI that are not entirely representative of a given region or of a particular vegetation type. The limitations imposed by available data for this region further compounds the problem in that the pre-historical fires are inserted based on a seven year burn record for Russia. The comparison between the results of *Zhuang et al.* [2006] and this study highlight the need for spatially explicit data sets on stand-age distribution in order to evaluate methodologies that estimate stand-age distributions prior to the start of historical fire data. It should be recognized that if stand age has been the result of multiple disturbances in a region, then the reconstruction of stand age distributions will need to consider the relevant set of disturbances in the region.

[47] A third challenge to incorporating fire into carbon balance estimates is related to the aboveground and ground layer carbon fraction consumed during a fire. Currently the definition of aboveground and ground layer carbon consumption and differentiating between fire regimes is limited to our understanding of what is presented in the literature and can therefore be taken only as a coarse estimate of what might actually be occurring in a given region. Also, the consumption parameters that we implemented in this study are fixed in time and do not take into account the seasonal variation in depth of burn. The importance of accounting for depth of burn is highlighted by *Kasischke et al.* [2005] and *Kasischke and Turetsky* [2006]; however, accounting for these seasonal differences in depth of burn will require that relationships among burn severity, seasonality of fire, and other factors be developed.

[48] An issue related to burn severity is the amount of nitrogen combusted from soil and vegetation nitrogen pools at the time of fire. Our assumption of 15% nitrogen loss from soil and vegetation at the time of fire is based on the assumption that nitrogen loss is highly variable across the boreal forest and in some cases can be reintroduced to the system by canopy ash [*Harden et al.*, 2004]. We conducted a sensitivity analysis that evaluated this uncertainty by assuming no retention of soil and vegetation nitrogen at the time of fire [see *Wang et al.*, 2001]. We found that across the pan-boreal region from 1996–2002, the effect of fire on carbon storage increased (i.e., became more of a source) by a factor of 50%, and decreased the overall carbon sink in response to all factors by 7%. Thus, in addition to better information on how burn severity influences carbon release, information on how burn severity influences nitrogen release would help improve the ability to represent interactions between how carbon and nitrogen affect carbon storage.

[49] The fourth challenge to incorporating fire into carbon balance estimates of the pan-boreal region is the role of peatland fires. Several studies have highlighted the importance of peatland fires in calculating current and future fire emissions [*Turetsky et al.*, 2002; *Kasischke and Turetsky*, 2006; *Turetsky et al.*, 2006]. With projections that some high-latitude regions will become drier in addition to warmer, it is possible that the fire regime will shift to later in the growing season, which may result in greater peatland fuel consumption with deeper thaw depths and therefore higher fire emissions. Therefore, it is important to accurately represent peatland burning in future studies to reduce uncertainties associated with estimating fire emissions.

5. Conclusion

[50] Our analysis suggests that CO_2, climate, and fire each are important in the carbon dynamics of the pan-boreal region at interannual, decadal, and multidecadal timescales. It also shows that it is important to incorporate fire in a

temporally and spatially explicit manner when simulating the effects of fire on carbon dynamics for the boreal forest. While our analysis does not consider the full suite of disturbances that occur in the pan-boreal region, our estimates are generally within the uncertainty of those presented in previous inversion-, inventory-, and process-based modeling studies within this region.

[51] Our analysis indicates that fire plays an important role in the interannual and decadal scale variability of source/sink relationships of the pan-boreal region. Other analyses indicate that changes in fire regime have the potential to substantially influence carbon source/sink relationships of northern terrestrial ecosystems at multidecadal to century timescales [*McGuire et al.*, 2004; *Zhuang et al.*, 2006]. While we found that the pan-boreal region acted as a carbon sink for the period 1996–2002 in response to CO_2, climate, and fire, with Eurasia accounting for more than half of this reported sink activity, fire in this time period tended to decrease the strength of the sink. Although we report that the pan-boreal region is currently acting as a net carbon sink when considering changes in atmospheric CO_2, climate and fire, there are substantial uncertainties in our estimates. These uncertainties are due to several factors which include sparse fire data across the Eurasian continent, uncertainty in estimating carbon consumption, and the difficulty in verifying assumptions about the representation of fires that occurred prior to the start of the historical fire record. The reduction of these uncertainties can be accomplished through the retrospective extension of the satellite-derived burn record in Eurasia back to the early 1980s using existing methods, better information on the spatial and temporal variability of above- and below-ground carbon fraction consumed, and the spatially explicit representation of stand age distribution throughout the pan-boreal region.

[52] It is currently difficult to project what the combined effects of increasing atmospheric CO_2, a changing climate dominated by increasing temperatures, and a changing fire regime dominated by increased burn severity, frequency, and size of fire will have on net carbon storage across boreal North America and Eurasia. If the proportion of large, severe fires increase as a result of a warmer climate, then the sink strength of northern terrestrial ecosystems may be weakened and potentially switch to becoming a carbon source to the atmosphere. Our ability to project future temporal and spatial changes in carbon dynamics at large spatial scales is limited by our understanding of how the temporal and spatial aspects of fire influence historical carbon dynamics. Further analyses of the retrospective role of fire in the pan-boreal region should include (1) improved data sets of fire area for Eurasia, (2) improved estimates of how carbon consumed by fire varies spatially and temporally, and (3) integration of fire with other important disturbances so that reconstructions of stand age based on assumptions about historical disturbance can be verified with data on current stand-age distributions.

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References

Amiro, B. D., J. M. Chen, and J. Liu (2000), Net primary productivity following forest fire for Canadian ecoregions, *Can. J. For. Res.*, *30*, 939–947.

Amiro, B. D., J. B. Todd, B. M. Wotton, K. A. Logan, M. D. Flannigan, B. J. Stocks, J. A. Mason, D. L. Martell, and K. G. Hirsch (2001), Direct carbon emissions from Canadian fires, *Can. J. For. Res.*, *31*, 512–525.

Bureau of Land Management (2005), Alaska fire history, 1950–2004, vector digital data, Alaska Fire Serv., Anchorage. (Available at http://agdc.usgs.gov/data/blm/fire/index.html)

Caspersen, J. P., S. W. Pacala, J. C. Jenkins, G. C. Hurtt, and P. R. Moorcroft (2000), Contributions of land-use history to carbon accumulation in U. S. forests, *Science*, *290*(5494), 1148–1151.

Chapin, F. S., III, et al. (2006), Reconciling carbon-cycle concepts, terminology, and methods, *Ecosystems*, *9*, 1041–1050.

Chapman, W. L., and J. E. Walsh (1993), Recent variations of sea ice and air temperatures in high latitudes, *Bull. Am. Meteorol. Soc.*, *74*, 33–47.

Chen, J., W. Chen, J. Liu, J. Cihlar, and S. Gray (2000), Annual carbon balance of Canada's forests during 1895–1996, *Global Biogeochem. Cycles*, *14*(3), 839–849.

Chen, J. M., W. Ju, J. Cihlar, D. Price, J. Liu, W. Chen, J. Pan, A. Black, and A. Barr (2003), Spatial distribution of carbon sources and sinks in Canada's forests, *Tellus, Ser. B*, *55*, 622–641.

Chen, J. M., B. Chen, K. Higuchi, J. Liu, D. Chan, D. Worthy, P. Tans, and A. Black (2006), Boreal ecosystems sequestered more carbon in warmer years, *Geophys. Res. Lett.*, *33*, L10803, doi:10.1029/2006GL025919.

Chen, W., J. M. Chen, D. T. Price, and J. Cihlar (2002), Effects of stand age on net primary productivity of boreal black spruce forests in Ontario, Canada, *Can. J. For. Res.*, *32*, 833–842.

Clein, J. S., B. Kwiatkowski, A. D. McGuire, J. E. Hobbie, E. B. Rastetter, J. M. Melillo, and D. W. Kicklighter (2000), Modeling carbon responses of tundra ecosystems to historical and projected climate: A comparison of a plot- and a global-scale ecosystem model to identify process-based uncertainties, *Global Change Biol.*, *6*, S127–S140.

Clein, J. S., A. D. McGuire, X. Zhang, D. W. Kicklighter, J. M. Melillo, S. C. Wofsy, P. G. Jarvis, and J. M. Massheder (2002), Historical and projected carbon balances of mature black spruce ecosystems across North America: The role of carbon-nitrogen interactions, *Plant Soil*, *242*, 15–32.

Conard, S. G., and G. A. Ivanova (1997), Wildfire in Russian boreal forests—Potential impacts of fire regime characteristics on emissions and global carbon balance estimates, *Environ. Pollut.*, *98*(3), 305–313.

Conard, S. G., A. I. Sukhinin, B. J. Stocks, D. R. Cahoon, E. P. Davidenko, and G. A. Ivanova (2002), Determining effects of area burned and fire severity on carbon cycling and emissions in Siberia, *Clim. Change*, *55*, 197–211.

Dargaville, R., A. D. McGuire, and P. Rayner (2002), Estimates of large-scale fluxes in high latitudes from terrestrial biosphere models and an inversion of atmospheric CO_2 measurements, *Clim. Change*, *55*, 273–285.

Dargaville, R., D. Baker, C. Rödenbeck, P. Rayner, and P. Ciais (2006), Estimating high latitude carbon fluxes with inversions of atmospheric CO_2, *Mitigation and Adaptation Strategies for Global Change*, *11*, doi:10.1007/s11027-005-9018-1.

DeLucia, E. H., D. J. Moore, and R. J. Norby (2005), Contrasting responses of forest ecosystems to rising atmospheric CO_2: Implications for the global C cycle, *Global Biogeochem. Cycles*, *19*, GB3006, doi:10.1029/2004GB002346.

Euskirchen, E. S., et al. (2006), Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems, *Global Change Biol.*, *12*, doi:10.1111/j.1365-2486.2006.01113.x.

FIRESCAN Science Team (1996), Fire in ecosystems of boreal Eurasia: The Bor Forest Island Fire Experiment, Fire Research Campaign Asia-North (FIRESCAN), in *Biomass Burning and Global Change*, vol. 2, edited by J. S. Levine, pp. 848–873, MIT Press, Cambridge, Mass.

Flannigan, M. D., and J. Little (2002), Canadian Large Fire Database, 1959–1999 point data set, Canadian Forest Service, Edmonton, Alberta, Canada. (Available at http://www.nofc.forestry.ca/fire/research/climate_change/lfdb/lfdb_download_e.htm)

Flannigan, M. D., Y. Bergeron, O. Engelmark, and B. M. Wotton (1988), Future wildfire in circumboreal forests in relation to global warming, *J. Veg. Sci.*, *9*, 469–476.

Flannigan, M. D., K. A. Logan, B. D. Amiro, W. R. Skinner, and B. J. Stocks (2005), Future area burned in Canada, *Clim. Change*, *72*, 1–16.

Forestry Canada (1992), Development and structure of the Canadian forest fire behavior prediction system, *Can. For. Serv. Inf. Rep.*, ST-X-3.

French, N. H. F., E. S. Kasischke, B. J. Stocks, J. P. Mudd, D. L. Martell, and B. S. Lee (2000), Carbon release from fires in the North American boreal forest, in *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*, *Ecol. Stud.*, vol. 138, edited by E. S. Kasischke and B. J. Stocks, pp. 377–388, Springer, New York.

French, N. H. F., E. S. Kasischke, and D. G. Williams (2002), Variability in the emission of carbon-based trace gases from wildfire in the Alaskan boreal forest, *J. Geophys. Res.*, *107*, 8151, doi:10.1029/2001JD000480 [printed *108*(D1), 2003].

Furyaev, V. V. (1996), *Role of Fires in Forest Forming Process* [in Russian], Nauka, Novosibirsk, Russia.

Gillett, N. P., A. J. Weaver, F. W. Zwiers, and M. D. Flannigan (2004), Detecting the effect of climate change on Canadian forest fires, *Geophys. Res. Lett.*, *31*, L18211, doi:10.1029/2004GL020876.

Global Soil Data Task Group (2000), Global gridded surfaces of selected soil characteristics (International Geosphere-Biosphere Programme-Data and Information System), Oak Ridge Natl. Lab. Distrib. Active Arch. Cent., Oak Ridge, Tenn.

Goetz, S. J., A. G. Bunn, G. J. Fiske, and R. A. Houghton (2005), Satellite observed photosynthetic trends across boreal North America associated with climate and fire disturbance, *Proc. Natl. Acad. Sci.*, *103*(38), 13,521–13,525.

Government of Alberta (2005), Historical wildfires: 1931–1979, Wildfire Resour. Inf. Sect., For. Prot. Div., Sustainable Resour. Dev., Edmonton, Alberta, Canada.

Gurney, K. R., et al. (2004), Transcom 3 inversion intercomparison: Model mean results for the estimation of seasonal carbon sources and sinks, *Global Biogeochem. Cycles*, *18*, GB1010, doi:10.1029/2003GB002111.

Harden, J. W., J. C. Neff, D. V. Sandberg, M. R. Turetsky, R. Ottmar, G. Gleixner, T. L. Fries, and K. L. Manies (2004), Chemistry of burning the forest floor during the FROSTFIRE experimental burn, interior Alaska, 1999, *Global Biogeochem. Cycles*, *18*, GB3014, doi:10.1029/2003GB002194.

Hicke, J. A., G. P. Asner, E. S. Kasischke, N. H. F. French, J. T. Randerson, G. J. Collatz, B. J. Stocks, C. J. Tucker, S. O. Los, and C. B. Field (2003), Postfire response of North American boreal forest net primary productivity analyzed with satellite observations, *Global Change Biol.*, *9*, 1145–1157.

Hungate, B. A., J. S. Dukes, M. R. Shaw, Y. Luo, and C. B. Field (2003), Nitrogen and climate change, *Science*, *302*(5650), 1512–1513.

Johnson, E. A. (1992), *Fire and Vegetation Dynamics: Studies From the North American Boreal Forest*, 129 pp., Cambridge Univ. Press, New York.

Kajii, Y., et al. (2002), Boreal forest fires in Siberia in 1998: Estimation of area burned and emissions of pollutants by advanced very high resolution radiometer satellite data, *J. Geophys. Res.*, *107*(D24), 4745, doi:10.1029/2001JD001078.

Kasischke, E. S., and L. P. Bruhwiler (2002), Emissions of carbon dioxide, carbon monoxide, and methane from boreal forest fires in 1998, *J. Geophys. Res.*, *107*, 8146, doi:10.1029/2001JD000461 [printed *108*(D1), 2003].

Kasischke, E. S., and M. R. Turetsky (2006), Recent changes in the fire regime across the North American boreal region—Spatial and temporal patterns of burning across Canada and Alaska, *Geophys. Res. Lett.*, *33*, L09703, doi:10.1029/2006GL025677.

Kasischke, E. S., N. L. Christensen Jr., and B. J. Stocks (1995), Fire, global warming, and the carbon balance of boreal forests, *Ecol. Appl.*, *5*(2), 437–451.

Kasischke, E. S., K. P. O'Neill, N. H. F. French, and L. L. Bourgeau-Chavez (2000), Controls on patterns of biomass burning in Alaskan boreal forests, in *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*, *Ecol. Stud.*, vol. 138, edited by E. S. Kasischke and B. J. Stocks, pp. 173–196, Springer, New York.

Kasischke, E. S., D. Williams, and D. Barry (2002), Analysis of the patterns of large fires in the boreal forest region of Alaska, *Int. J. Wildland Fire,*, *11*, 131–144.

Kasischke, E. S., E. J. Hyer, P. C. Novelli, L. P. Bruhwiler, N. H. F. French, A. I. Sukhinin, J. H. Hewson, and B. J. Stocks (2005), Influences of boreal fire emissions on Northern Hemisphere atmospheric carbon and carbon monoxide, *Global Biogeochem. Cycles*, *19*, GB1012, doi:10.1029/2004GB002300.

Keeling, C. D., and T. P. Whorf (2005), Atmospheric CO_2 records from sites in the SIO air sampling network, in *Trends: A Compendium of Data on Global Change*, Carbon Dioxide Inf. Anal. Cent., Oak Ridge Natl. Lab., U.S. Dep. of Energy, Oak Ridge, Tenn.

Kicklighter, D. W., et al. (1999), A first-order analysis of the potential role of CO_2 fertilization to affect the global carbon budget: A comparison of four terrestrial biosphere models, *Tellus, Ser. B*, *51*, 343–366.

Kimball, J. S., K. C. McDonald, and M. Zhao (2006), Spring thaw and its effect on terrestrial vegetation productivity in the western Arctic observed from satellite microwave and optical remote sensing, *Earth Interactions*, *10*, 1–22. (Available at http://earthinteractions.org)

Kimball, J. S., et al. (2007), Recent climate driven increases in vegetation productivity for the western Arctic: Evidence of an acceleration of the northern terrestrial carbon cycle, *Earth Interactions*, *11*, 1–30. (Available at http://earthinteractions.org)

Kurz, W. A., and M. J. Apps (1999), A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector, *Ecol. Appl.*, *9*(2), 526–547.

Luo, Y., et al. (2004), Progressive nitrogen limitation of ecosystem responses to rising atmospheric carbon dioxide, *BioScience*, *54*(8), 731–739.

McCoy, V. M., and C. R. Burn (2005), Potential alteration by climate change of the forest-fire regime in the boreal forest of Central Yukon Territory, *Arctic*, *58*(3), 276–285.

McGuire, A. D., J. M. Melillo, L. A. Joyce, D. W. Kicklighter, A. L. Grace, B. Moore III, and C. J. Vorosmarty (1992), Interactions between carbon and nitrogen dynamics in estimating net primary productivity for potential vegetation in North America, *Global Biogeochem. Cycles*, *6*, 101–124.

McGuire, A. D., L. A. Joyce, D. W. Kicklighter, J. M. Melillo, G. Esser, and C. J. Vorosmarty (1993), Productivity response of climax temperate forests to elevated temperature and carbon dioxide: A North American comparison between two global models, *Clim. Change*, *24*, 287–310.

McGuire, A. D., J. M. Melillo, D. W. Kicklighter, Y. Pan, X. Xiao, J. Helfrich, B. Moore III, C. J. Vorosmarty, and A. L. Schloss (1997), Equilibrium responses of global net primary production and carbon storage to doubled atmospheric carbon dioxide: Sensitivity to changes in vegetation nitrogen concentration, *Global Biogeochem. Cycles*, *11*, 173–189.

McGuire, A. D., J. Clein, J. M. Melillo, D. W. Kicklighter, R. A. Meier, C. J. Vorosmarty, and M. C. Serreze (2000a), Modeling carbon responses of tundra ecosystems to historical and projected climate: The sensitivity of pan-arctic carbon storage to temporal and spatial variation in climate, *Global Change Biol.*, *6*, S141–S159.

McGuire, A. D., J. M. Melillo, J. T. Randerson, W. J. Parton, M. Heimann, R. A. Meier, J. S. Clein, D. W. Kicklighter, and W. Sauf (2000b), Modeling the effects of snowpack on heterotrophic respiration across northern temperate and high latitude regions: Comparison with measurements of atmospheric carbon dioxide in high latitudes, *Biogeochemistry*, *48*, 91–114.

McGuire, A. D., et al. (2001), Carbon balance of the terrestrial biosphere in the twentieth century: Analyses of CO_2, climate and land use effects with four process-based ecosystem models, *Global Biogeochem. Cycles*, *15*(1), 183–206.

McGuire, A. D., et al. (2002), Environmental variation, vegetation distribution, carbon dynamics and water/energy exchange at high latitudes, *J. Veg. Sci.*, *13*, 301–314.

McGuire, A. D., et al. (2004), Land cover disturbances and feedbacks to the climate system in Canada and Alaska, in *Land Change Science: Observing, Monitoring, and Understanding Trajectories of Change on the Earth's Surface*, edited by G. Gutman et al., pp. 139–161, Kluwer Acad., Dordrecht, Netherlands.

McGuire, A. D., F. S. Chapin III, J. E. Walsh, and C. Wirth (2006), Integrated regional changes in arctic climate feedbacks: Implications for the global climate system, *Ann. Rev. Environ. Resour.*, *31*, 61–91.

Melillo, J. M., A. D. McGuire, D. W. Kicklighter, B. Moore III, C. J. Vorosmarty, and A. L. Schloss (1993), Global climate change and terrestrial net primary production, *Nature*, *63*, 234–240.

Mitchell, T. D., and P. D. Jones (2005), An improved method of constructing a database of monthly climate observations and associated high-resolution grids, *Int. J. Climatol.*, *25*(6), 693–712.

Mouillot, F., A. Narasimha, Y. Balkanski, J.-F. Lamarque, and C. B. Field (2006), Global carbon emissions from biomass burning in the 20th century, *Geophys. Res. Lett.*, *33*, L01801, doi:10.1029/2005GL024707.

Myneni, R. B., J. Dong, C. J. Tucker, R. K. Kaufmann, P. E. Kauppi, J. Liski, L. Zhou, V. Alexeyev, and M. K. Hughes (2001), A large carbon sink in the woody biomass of northern forests, *Proc. Natl. Acad. Sci.*, *98*, 14,784–14,789.

Naelapea, O., and J. Nickeson (1998), SERM forest fire chronology of Saskatchewan in vector format, Oak Ridge Natl. Lab. Distrib. Active Arch. Cent., Oak Ridge, Tenn.

National Geophysical Data Center (NGDC) (1994), TerrainBase v. 1.1, 5-minute digital terrain model data, Boulder, Colo.

Nemani, R. R., C. D. Keeling, H. Hashimoto, W. M. Jolly, S. C. Piper, C. J. Tucker, R. B. Myneni, and S. W. Running (2003), Climate-driven increases in global terrestrial net primary production from 1982–1999, *Science*, *300*, 1560–1563.

Norby, R. J., et al. (2005), Forest response to elevated CO_2 is conserved across a broad range of productivity, *Proc. Natl. Acad. Sci.*, *102*(50), 18,052–18,056.

Peng, C., and M. J. Apps (1999), Modelling the response of net primary productivity (NPP) of boreal forest ecosystems to changes in climate and fire disturbance regimes, *Ecol. Modell.*, *122*, 175–193.

Potter, C., P.-N. Tan, M. Steinbach, S. Klooster, V. Kumar, R. Myneni, and V. Genovese (2003a), Major disturbance events in terrestrial ecosystems detected using global satellite data sets, *Global Change Biol.*, *9*, 1005–1021.

Potter, C., S. Klooster, P. Tan, M. Steinbach, V. Kumar, and V. Genovese (2003b), Variability in terrestrial carbon sinks over two decades. Part 1: North America, *Earth Interactions*, *7*, 1–14.

Potter, C., S. Klooster, P. Tan, M. Steinbach, V. Kumar, and V. Genovese (2005), Variability in terrestrial carbon sinks over two decades: Part 2–Eurasia, *Global Planet. Change*, *49*, 177–186.

Raich, J. W., E. B. Rastetter, J. M. Melillo, D. W. Kicklighter, P. A. Steudler, B. J. Peterson, A. L. Grace, B. Moore III, and C. J. Vörösmarty (1991), Potential net primary productivity in South America: Application of a global model, *Ecol. Appl.*, *1*(4), 399–429.

Schimel, D. S., et al. (2001), Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems, *Nature*, *414*, 169–172.

Serreze, M. C., and J. A. Francis (2006), The Arctic amplification debate, *Clim. Change*, *76*, 241–264.

Serreze, M. C., J. E. Walsh, F. S. Chapin III, T. Osterkamp, M. Dyurgerov, V. Romanovsky, W. C. Oechel, J. Morison, T. Zhang, and R. G. Barry (2000), Observational evidence of recent change in the northern high-latitude environment, *Clim. Change*, *46*, 159–207.

Shvidenko, A. Z., and S. Nilsson (2000), Fire and the carbon budget of Russian forests, in *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*, *Ecol. Stud.*, vol. 138, edited by E. S. Kasischke and B. J. Stocks, pp. 289–311, Springer, New York.

Shvidenko, A., and S. Nilsson (2002), Dynamics of Russian forests and the carbon budget in 1961–1998: An assessment based on long-term forest inventory data, *Clim. Change*, *55*, 5–37.

Shvidenko, A., and S. Nilsson (2003), A synthesis of the impact of Russian forests on the global carbon budget for 1961–1998, *Tellus, Ser. B*, *55*, 391–415.

Soja, A. J., W. R. Cofer, H. H. Shugart, A. I. Sukhinin, P. W. Stackhouse Jr, D. J. McRae, and S. G. Conard (2004), Estimating fire emissions and disparities in boreal Siberia (1998–2002), *J. Geophys. Res.*, *109*, D14S06, doi:10.1029/2004JD004570.

Stocks, B. J., et al. (1998), Climate change and forest fire potential in Russian and Canadian boreal forests, *Clim. Change*, *38*, 1–13.

Sukhinin, A. I., et al. (2004), AVHRR-based mapping of fires in Russia: New products for fire management and carbon cycle studies, *Remote Sens. Environ.*, *93*(4), 546–564.

Thompson, C. D., A. D. McGuire, J. S. Clein, F. S. Chapin III, and J. Beringer (2006), Net carbon exchange across the arctic tundra-boreal forest transition in Alaska 1981–2000, *Mitigation and Adaptation Strategies for Global Change*, *11*, 805–827.

Thonicke, K., S. Venevsky, S. Sitch, and W. Cramer (2001), The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model, *Global Ecol. Biogeogr.*, *10*, 661–677.

Tian, H., J. M. Melillo, D. W. Kicklighter, A. D. McGuire, and J. Helfrich (1999), The sensitivity of terrestrial carbon storage to historical climate variability and atmospheric CO_2 in the United States, *Tellus, Ser. B*, *51*, 414–452.

Turetsky, M., K. Wieder, L. Halsey, and D. Vitt (2002), Current disturbance and the diminishing peatland carbon sink, *Geophys. Res. Lett.*, *29*(11), 1526, doi:10.1029/2001GL014000.

Turetsky, M. R., J. Harden, H. R. Friedli, M. Flannigan, N. Payne, J. Crock, and L. Radke (2006), Wildfires threaten mercury stocks in northern soils, *Geophys. Res. Lett.*, *33*, L16403, doi:10.1029/2005GL025595.

Turner, M. G., and W. H. Romme (1994), Landscape dynamics in crown fire ecosystems, *Landscape Ecol.*, *9*(1), 59–77.

van der Werf, G. R., J. T. Randerson, L. Giglio, G. J. Collatz, P. S. Kasibhatla, and A. F. Arellano Jr. (2006), Interannual variability in global biomass burning emissions from 1997 to 2004, *Atmos. Chem. Phys.*, *6*, 3423–3441.

Venevsky, S., K. Thonicke, S. Sitch, and W. Cramer (2002), Simulating fire regimes in human-dominated ecosystems: Iberian Peninsula case study, *Global Change Biol.*, *8*, 984–998.

Wang, S., D. Hui, and Y. Luo (2001), Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: A meta-analysis, *Ecol. Appl.*, *11*(5), 1349–1365.

Weber, M. G., and M. D. Flannigan (1997), Canadian boreal forest ecosystem structure and function in a changing climate: Impact on fire regimes, *Environ. Rev.*, *5*, 145–166.

Wirth, C. (2005), Fire regime and tree diversity in boreal forests: Implications for the carbon cycle, in *Forest Diversity and Function: Temperate and Boreal Systems*, *Ecol. Stud.*, vol. 176, edited by M. Scherer-Lorenzen, C. Körner, and E.-D. Schulze, pp. 309–344, Springer, Berlin.

Wirth, C., E.-D. Schulze, B. Lühker, S. Grigoriev, M. Siry, G. Hardes, W. Ziegler, M. Backor, G. Bauer, and N. N. Vygodskaya (2002a), Fire and site type effects on the long-term carbon and nitrogen balance in pristine Siberian Scots pine forests, *Plant Soil*, *242*, 41–63.

Wirth, C., C. I. Czimczik, and E. D. Schulze (2002b), Beyond annual budgets: Carbon flux at different temporal scales in fire-prone Siberian Scots pine forests, *Tellus, Ser. B*, *54*, 611–630.

Wotton, B. M., and M. D. Flannigan (1993), Length of the fire season in a changing climate, *For. Chron.*, *69*, 187–192.

Wotton, B. M., D. L. Martell, and K. A. Logan (2003), Climate change and people-caused forest fire occurrence in Ontario, *Clim. Change*, *60*, 275–295.

Xiao, X., D. W. Kicklighter, J. M. Melillo, A. D. McGuire, P. H. Stone, and A. P. Sokolov (1997), Linking a global terrestrial biogeochemical model and a 2-dimensional climate model: Implications for the carbon budget, *Tellus, Ser. B*, *49*, 18–37.

Yurganov, L. N., et al. (2004), A quantitative assessment of the 1998 carbon monoxide emission anomaly in the Northern Hemisphere based on total column and surface concentration measurements, *J. Geophys. Res.*, *109*, D15305, doi:10.1029/2004JD004559.

Zhuang, Q., V. E. Romanovsky, and A. D. McGuire (2001), Incorporation of a permafrost model into a large-scale ecosystem model: Evaluation of temporal and spatial scaling issues in simulating soil thermal dynamics, *J. Geophys. Res.*, *106*, 33,649–33,670.

Zhuang, Q., A. D. McGuire, J. Harden, K. P. O'Neill, V. E. Romanovsky, and J. Yarie (2002), Modeling soil thermal and carbon dynamics of a fire chronosequence in interior Alaska, *J. Geophys. Res.*, *107*, 8147, doi:10.1029/2001JD001244 [printed *108*(D1), 2003].

Zhuang, Q., et al. (2003), Carbon cycling in extratropical terrestrial ecosystems of the Northern Hemisphere during the 20th century: A modeling analysis of the influences of soil thermal dynamics, *Tellus, Ser. B*, *55*, 751–776.

Zhuang, Q., J. M. Melillo, B. S. Felzer, D. W. Kicklighter, A. D. McGuire, M. C. Sarofim, A. Sokolov, R. G. Prinn, P. A. Steudler, and S. Hu (2006), CO_2 and CH_4 exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st century, *Geophys. Res. Lett.*, *33*, L17403, doi:10.1029/2006GL026972.

M. Apps and W. A. Kurz, Natural Resources Canada, Canadian Forest Service, Victoria, BC, Canada V8Z 1M5.

M. S. Balshi, Department of Biology and Wildlife, University of Alaska Fairbanks, Fairbanks, AK 99775, USA.

T. J. Burnside, J. S. Clein, and J. McAllister, Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK 99775, USA.

M. Flannigan, Great Lakes Forestry Centre, Canadian Forest Service, Sault Ste. Marie, ON, Canada P6A 2E5.

J. Harden, U.S. Geological Survey, Menlo Park, CA 94025, USA.

E. Kasischke, Department of Geography, University of Maryland at College Park, College Park, MD 20742, USA.

D. W. Kicklighter and J. Melillo, Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA 02543, USA.

A. D. McGuire, Alaska Cooperative Fish and Wildlife Research Unit, U.S. Geological Survey, University of Alaska Fairbanks, Fairbanks, AK 99775, USA.

A. Shvidenko, International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria.

C. Wirth, Max-Planck-Institute for Biogeochemistry, D-07743 Jena, Germany.

Q. Zhuang, Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907, USA.