Is the northern high-latitude land-based CO_2 sink weakening?

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[1] Studies indicate that, historically, terrestrial ecosystems of the northern high-latitude region may have been responsible for up to 60% of the global net land-based sink for atmospheric CO_2. However, these regions have recently experienced remarkable modification of the major driving forces of the carbon cycle, including surface air temperature warming that is significantly greater than the global average and associated increases in the frequency and severity of disturbances. Whether Arctic tundra and boreal forest ecosystems will continue to sequester atmospheric CO_2 in the face of these dramatic changes is unknown. Here we show the results of model simulations that estimate a 41 Tg C yr^{-1} sink in the boreal land regions from 1997 to 2006, which represents a 73% reduction in the strength of the sink estimated for previous decades in the late 20th century. Our results suggest that CO_2 uptake by the region in previous decades may not be as strong as previously estimated. The recent decline in sink strength is the combined result of (1) weakening sinks due to warming-induced increases in soil organic matter decomposition and (2) strengthening sources from pyrogenic CO_2 emissions as a result of the substantial area of boreal forest burned in wildfires across the region in recent years. Such changes create positive feedbacks to the climate system that accelerate global warming, putting further pressure on emission reductions to achieve atmospheric stabilization targets.

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1. Introduction

[2] Terrestrial ecosystems act as a key control on climate warming by sequestering in plants and soil a significant portion of anthropogenic CO_2 emissions, which have been deemed primarily responsible for the increase in global surface air temperature since the mid-20th century [*Intergovernmental Panel on Climate Change*, 2007]. The northern high-latitude region is generally thought to be acting as a considerable land-based sink for atmospheric CO_2, based on the results from both "top-down" and "bottom-up" approaches to regional C budget estimates [*McGuire et al.*, 2009]. However, the precise role that the northern high-latitude region plays in the global carbon budget is not well understood, owing to the uncertainties associated with (1) the different methodologies employed to estimate regional C fluxes and (2) the sensitivity of these fluxes to changes in the various controlling mechanisms of the high-latitude C cycle. A recent analysis that provides new constraints on the latitudinal distribution of CO_2 fluxes suggests that uptake by the northern extratropical land regions may not be as large as previously estimated [*Stephens et al.*, 2007], and there is concern about the uncertain future of the global terrestrial CO_2 sink response to climate change [*Le Quéré et al.*, 2009; *Canadell et al.*, 2007a; *Fung et al.*, 2005].

[3] A recent review of bottom-up inventory- and process-based carbon budget analyses suggests that Arctic and boreal ecosystems in the northern high latitudes have been responsible for storing on the order of 0.3 to 0.6 Pg C yr^{-1} over the late 20th century [*McGuire et al.*, 2009], which represents a significant portion of the estimated 1.0 Pg C yr^{-1} net land-based sink of atmospheric CO_2 during the 1990s [*Denman et al.*, 2007]. Estimates based on inventory data and process models show North American high-latitude forests (i.e., in Canada and Alaska) as near-neutral to a small sink for the latter part of the 20th century [*Balshi et al.*, 2007; *Chen et al.*, 2000; *Kurz and Apps*, 1999; *Myneni et al.*, 2001]. Inventory-based assessments suggest a larger net C uptake in Eurasian forests over the late 20th century [*Beer et al.*, 2006; *Goodale et al.*, 2002; *Liski et al.*, 2002, 2003; *Myneni et al.*, 2001; *Shvidenko and Nilsson*, 2002, 2003]. The majority of the sink

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activity suggested by these inventory studies is through C storage in vegetation pools [*Liski et al.*, 2003; *Myneni et al.*, 2001; *Shvidenko and Nilsson*, 2002], while the effect of soil organic matter dynamics on regional C balance remains highly uncertain with inventory-based methods.

[4] Model means from top-down methods, based on precise measurements of atmospheric [CO_2] and inverse models of atmospheric transport, show a range of sink estimates for high-latitude regions of North America and Eurasia from 0.16 to 0.4 Pg C yr^{-1} during the 1990s [*Baker et al.*, 2006; *Gurney et al.*, 2004; *Rödenbeck et al.*, 2003]. Large uncertainties around these mean estimates, however, make it difficult to ascertain even the direction of the net flux using these methods. The uncertainties of atmospheric inversion approaches to estimating CO_2 exchange in northern high-latitude regions are reviewed by *Dargaville et al.* [2006], including those associated with a sparse measurement network over the region. In particular, inverse estimates of CO_2 fluxes in boreal Asia appear to be very sensitive to the initial estimates used as starting points for the inversions [*Dargaville et al.*, 2002, 2006]. Furthermore, *Stephens et al.* [2007] demonstrate that taking results from a subset of inverse models that most accurately represent vertical profiles of [CO_2] would suggest a smaller northern extratropical land-based sink than previously estimated.

[5] Many key processes in high-latitude ecosystems are sensitive to climate change [*McGuire et al.*, 2006], and the region has experienced surface air temperature warming that is significantly greater than the global average in recent decades [*Euskirchen et al.*, 2007; *Polyakov et al.*, 2002; *Serreze and Francis*, 2006]. Coupled climate-carbon model simulations predict that the northern high latitudes will serve as a substantial land carbon sink during the 21st century because both climate warming and elevated global [CO_2] favor increased productivity and CO_2 uptake in the region [*Friedlingstein et al.*, 2006; *Qian et al.*, 2010; *Sitch et al.*, 2008]. Observational, experimental and modeling studies suggest a trend of increasing productivity in Arctic and boreal vegetation in response to CO_2 fertilization [*Norby et al.*, 2005; *Oechel et al.*, 2000], nitrogen deposition [*Magnani et al.*, 2007], longer growing seasons [*Piao et al.*, 2007], and the expansion of woody vegetation [*Sturm et al.*, 2001]. However, other studies suggest that this response can be attenuated by factors such as drought stress [*Goetz et al.*, 2005] and N limitation [*Jain et al.*, 2009; *Sokolov et al.*, 2008]. While C gains in vegetation pools can be expected from increased productivity, storage in soil organic matter pools in high-latitude ecosystems is a function of complex interactions between soil thermal properties and permafrost dynamics [*Euskirchen et al.*, 2006; *Schuur et al.*, 2009; *Zhuang et al.*, 2003]. Furthermore, many of these studies do not consider the impacts of disturbance on C balance, yet evidence suggests changing disturbance regimes in the region [*Kasischke and Turetsky*, 2006; *Soja et al.*, 2007; *Flannigan et al.*, 2006], which lead to uncertainty in the region's future role as a CO_2 sink [*Kurz et al.*, 2008a]. Multiple lines of evidence have recently emerged that indicate the potential for large C losses from high-latitude ecosystems due to increases in wildfire [*Balshi et al.*, 2009; *Bond-Lamberty et al.*, 2007; *Tchebakova et al.*, 2009] and insect outbreaks [*Kurz et al.*, 2008b].

[6] As the changes in these driving forces of C dynamics vary in time and space over the region, their combined impact on the operation of the contemporary northern high-latitude land sink is not well understood. A key question is whether Arctic tundra and boreal forest ecosystems will continue to sequester atmospheric CO_2 in the face of these changes. Ecological principles dictate that the strength of the CO_2 sink can be altered in response to any mechanism that changes the balance between C uptake and release through biogeochemical processes in terrestrial ecosystems [*Canadell et al.*, 2007b]. With multiple lines of evidence emerging on the response of high-latitude C dynamics to changes in these individual, often competing driving factors, a comprehensive and integrated view of the overall impact of these factors on the strength of the regional CO_2 sink is needed. Here, we take a process-based approach that incorporates the major controlling factors in a model analysis of the response of the northern high-latitude land-based CO_2 sink to these recent changes.

2. Methods

[7] Retrospective simulations of ecosystem dynamics in the northern high-latitude land region were conducted using the Terrestrial Ecosystem Model (TEM), a coupled carbon-nitrogen biogeochemical process model [*Raich et al.*, 1991], to investigate the impacts of recent changes in atmospheric [CO_2], tropospheric ozone levels (O_3), N deposition and climate variability, as well as fire, forest management and agricultural land use regimes on the land-atmosphere exchange of CO_2 in Arctic and boreal ecosystems. We focus this analysis on the relative importance of these factors on controlling land-atmosphere CO_2 exchange across the major broad "ecozone" types within three subregions, considered here as the boreal North America (BONA) and boreal Asia (BOAS) regions, defined by the land base functions of the Transcom atmospheric inversion model experiments [*Gurney et al.*, 2002], and the boreal Europe (BOEU) region, defined as the land area within Norway, Sweden, Finland and European Russia (Figure 1).

[8] Sink strength is estimated by a measure of the vertical exchange of CO_2 between the land and the atmosphere as simulated by TEM, here referred to as net ecosystem exchange (NEE). NEE, a negative value of which represents a CO_2 sink in the terrestrial ecosystem, is the balance between C uptake in vegetation though net primary production (NPP) and C release via the heterotrophic respiration (HR) of soil organic matter, CO_2 emissions from fires, and the decay of harvested forest and agricultural products. Because the TEM estimates total C emissions associated with biomass burning [see *Balshi et al.*, 2007], we partitioned the total emissions into pyrogenic emissions of CO_2, CH_4, and CO. The proportion of flaming versus smoldering emissions were determined using ratios for vegetation (80% flaming: 20% smoldering) and soil (20%: 80%) carbon converted in fire, based on the work of *Kasischke and Bruhwiler* [2002]. The mean emission factors reported by *French et al.* [2002] were used to calculate the amount of each gas released in fires. Only pyrogenic CO_2 emissions are included in the calculation of NEE, i.e., the vertical land-atmosphere exchange of C as CO_2; C emitted as CH_4 (f_{CH4}) and CO (f_{CO}), as well as in the lateral transfer of dissolved organic

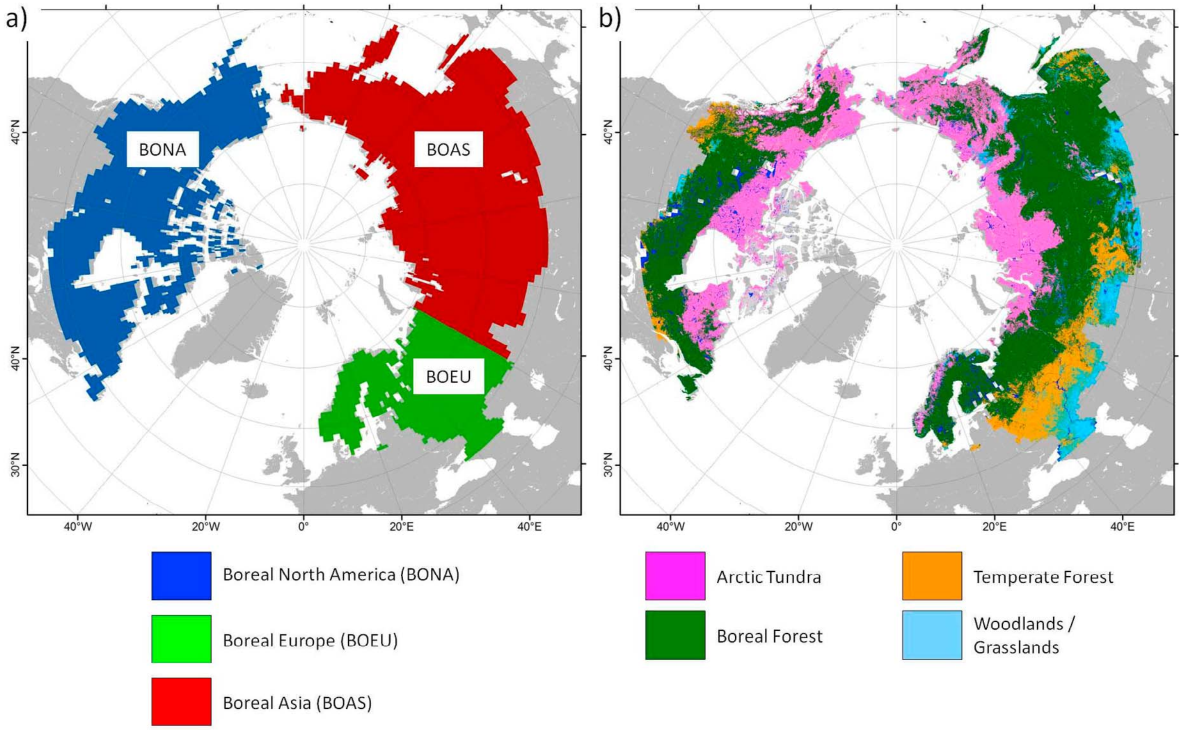

Figure 1. Maps showing (a) the location of the boreal land regions used in this study: boreal North America (BONA), boreal Europe (BOEU), and boreal Asia (BOAS); and (b) the spatial distribution of the major ecozones (based on potential vegetation) across the northern high latitudes.

carbon (f_{DOC}), is tracked in the net ecosystem C balance (NECB) [see *Chapin et al.*, 2006] for mass balance purposes in the TEM. Fluxes of f_{CH4} and f_{CO} and f_{DOC} are not included in the NEE estimates reported in this study.

2.1. Model Description

[9] The TEM is well-documented and has been used to examine patterns of terrestrial C dynamics across the globe, including how they are influenced by multiple factors such as CO_2 fertilization, climate change and variability, row-crop agriculture, wildfire and O_3 pollution [e.g., *Balshi et al.*, 2007; *Euskirchen et al.*, 2006; *Felzer et al.*, 2005; *McGuire et al.*, 2000a; *Zhuang et al.*, 2006]. Model estimates of flux variables and process representations in TEM have been extensively evaluated in numerous studies at site [e.g., *Amthor et al.*, 2001; *Clein et al.*, 2000; *Zhuang et al.*, 2002] and regional [e.g., *Balshi et al.*, 2007; *McGuire et al.*, 2000b; *Dargaville et al.*, 2002; *Zhuang et al.*, 2003] scales. Additional detail on model evaluations is given in Text S1.[1]

[10] For this study, we used a version of TEM that has been modified from *Felzer et al.* [2004], which simulated CO_2 fertilization, O_3 pollution, climate and row-crop agriculture effects, to also include the influence of permafrost dynamics [*Euskirchen et al.*, 2006; *Zhuang et al.*, 2003], atmospheric N deposition, dissolved organic carbon (DOC) leaching, wildfire, pastures and timber harvest on terrestrial carbon dynamics. To simulate the effects of N deposition, atmospheric NH_X and NO_Y prescribed from spatially explicit time series data sets are added to the available N pool within TEM for potential uptake by microbes and vegetation. DOC is assumed to be produced by the incomplete decomposition of soil organic matter (SOM) and f_{DOC} is associated with water yield from the ecosystem. The treatment of permafrost dynamics, and their influence on the availability of SOM for decomposition, has also been modified in this new version of TEM. Instead of a fixed rooting depth, the amount of SOM available for decomposition in a particular month is determined by the proportion of the SOM found within a varying active layer depth. As the permafrost thaws and the active layer depth increases, the relative amount of SOM available to decompose increases. See Text S1 for more information on how carbon uptake, decomposition, and DOC dynamics are simulated in this updated version of TEM.

[11] The TEM is calibrated to site-specific vegetation parameters [*Clein et al.*, 2000; *Euskirchen et al.*, 2006; *Raich et al.*, 1991] and extrapolated across the study area based on spatially explicit time series data organized on a 0.5° latitude by 0.5° longitude grid. The model is driven by spatially referenced information on atmospheric chemistry, climate, elevation, soils, and land cover to estimate monthly terrestrial C, N, and water fluxes and pool sizes. Spatially and temporally explicit data sets on these controlling factors were assembled to cover the pan-Arctic terrestrial region (north of 45°N latitude) as defined by *McGuire et al.* [2009], which integrates astronomical, climatic, cryospheric and hydrologic definitions of the Arctic system. In this study, we simulate terrestrial C dynamics under four different land uses (natural, row-crop agriculture, pasture, timber harvest) along with the influence of wildfire and the conversion of land from one

[1]Auxiliary materials are available with the HTML. doi:10.1029/2010GB003813.

use to another on these dynamics. The simulation of these dynamics by TEM have been described previously for natural ecosystems [*Melillo et al.*, 1993; *Tian et al.*, 1999], row-crop agriculture [*Felzer et al.*, 2004], wildfire [*Balshi et al.*, 2007], and the conversion and abandonment of agricultural land uses [*Galford et al.*, 2011; *McGuire et al.*, 2001].

2.2. Driving Data

[12] To extrapolate the model simulations across the pan-Arctic region, we incorporated driving data sets that have (1) spatial variability, but no temporal variability (elevation and soil texture); (2) temporal variability, but no spatial variability (atmospheric CO_2 concentration); and (3) temporal and spatial variability (air temperature, precipitation, solar radiation, AOT40 ozone index, atmospheric N deposition, and land cover including fire disturbance). The nontemporally varying spatial data sets were aggregated to 0.5° spatial resolution, with elevation based on the TerrainBase v1.1 data set the National Geophysical Data Center, Boulder, Colorado, United States [*National Geophysical Data Center*, 1994] and soil texture from the Global Gridded Surfaces of Selected Soil Characteristics data set [*Global Soil Data Set Task Group*, 2000].

[13] Most of the temporally varying data sets have been used in previous studies, but needed to be extended from 2000 or 2002 to 2006, as well as "back-casted" to year 1000 of the model initialization period, for use in this study. Global annual atmospheric CO_2 data are from the Mauna Loa station [*Keeling and Whorf*, 2005]. Atmospheric [CO_2] for the time period of years 1000 to 1900 was held constant at the year 1901 level (296.3 ppm). Monthly air temperature (°C), precipitation (mm), and incident short-wave solar radiation (Wm^{-2}) data derived from observations for the period 1901–2002, gridded at 0.5° resolution, were obtained from the Climate Research Unit (CRU; University of East Anglia, United Kingdom) [*Mitchell and Jones*, 2005]. The CRU climate variables were extended to 2006 with NCEP/NCAR Reanalysis 1 data sets (NOAA-ESRL Physical Sciences Division, Boulder CO) using a regression procedure based on data anomalies [*Drobot et al.*, 2006] from a 10 year (1993–2002) mean for each variable. These data sets were back-casted to year 1000 by a repeating 30 year cycle of the 1901–1930 monthly data to initialize the C pools with climate variability (except for the simulation without climate variability, where 1901–1930 monthly means were used to drive the model for each year). The ozone (O_3) pollution data set used in this study, represented by a measure of the accumulated hourly ozone levels above a threshold of 40 ppb (AOT40 index), is based on the work of *Felzer et al.* [2005] and covers the time period from 1860 to 2006. Before 1860, the ozone level in each 0.5° grid cell was assumed to equal the AOT40 of 1860 (which is equal to zero). The atmospheric N deposition data were based on the work of *Van Drecht et al.* [2003], extended from 2000 to 2006 by adding the difference in annual N deposition rate from 1999 to 2000 to succeeding years, for each 0.5° grid cell (e.g., 2001 N deposition rate = 2000 + (2000–1999), etc.). For years 1000 to 1859, annual N deposition was assumed to equal the per grid cell rates in 1860.

[14] To represent the influence of disturbance and land use change on terrestrial carbon dynamics, TEM now uses a dynamic cohort approach. In this approach, TEM initially assumes a grid cell is covered by undisturbed natural vegetation, or "potential vegetation," which is represented by initial cohorts that collectively sum to the entire land area of the grid cell (see Text S1 for a description of the potential vegetation data set). When a disturbance occurs, a new cohort is formed and a certain amount of land area within the grid cell is then subtracted from the potential vegetation cohort and assigned to the new disturbed cohort. As time progresses in the TEM simulation and more disturbances occur, more cohorts are added to the grid cell. As each disturbance and its effects are tracked separately within TEM, different types of disturbances within a grid cell can be considered simultaneously and allows TEM to consider the impacts of multiple disturbances on terrestrial C and N dynamics.

[15] The location and timing of disturbances are determined from data sets on fire occurrence, area burned, fire severity, and fire return interval, as well as modeled data for rates of forest harvest and crop and pasture establishment and abandonment. Historical annual burn areas for North America from 1950–2002 were available from the Alaska and Canada fire databases compiled for the study by *Balshi et al.* [2007]. The annual area burned data set for Eurasia was based on Advanced Very High Resolution Radiometer (AVHRR) satellite-derived fire scars data from 1996–2002 [*Sukhinin et al.*, 2004]. To cover the full temporal extent of the model spin-up period, these data were back-casted to the year 1000 based on 0.5° resolution fire return intervals. For a complete description of the historical fire data set, fire return interval calculation, and back-casting approach, see *Balshi et al.* [2007]. That study's fire data sets were extended from 2002 to 2006 with updated data from the U.S. Department of the Interior Bureau of Land Management [*Alaska Fire Service*, 2005] for Alaska and the Canadian Large Fire Database [*Flannigan and Little*, 2005]. The data were extended for Eurasia using the Global Fire Emission Database version 2 [*Randerson et al.*, 2006; *van der Werf et al.*, 2006]. This data set provides monthly burn fraction by 1° × 1° grid cell, which was converted to annual burn area and extracted from cohorts based on a priority list of burnable ecosystem types and age classes, thereby creating a new, secondary cohort of age zero for that year. In the same way, forest harvest and land use (crops or pasture) cohorts were created in the input data set, derived from 1° × 1° gridded, annual land use transitions data for years 1700 through 2000, modeled by *Hurtt et al.* [2006]. For Eurasia, the land use transitions data set was back-casted to the start of the initialization period by linearly "ramping-up" the transitions rates from 0% per year (for each 1° × 1° grid cell) starting in year 1000 to the year 1700 rates. For North America, we assumed land use transition rates of 0% prior to the year 1700. For both regions, the data were extended by simply using the 2000 rates for year 2001 to 2006.

2.3. The Simulation Framework

[16] Model experiments can be used to assess the influence of individual driving factors on C dynamics and quantify their effects [*McGuire et al.*, 2001]. To quantify the effects of the various controlling factors considered in this study on terrestrial C dynamics across the high-latitude region, we conducted a series of seven model simulations. The simulation

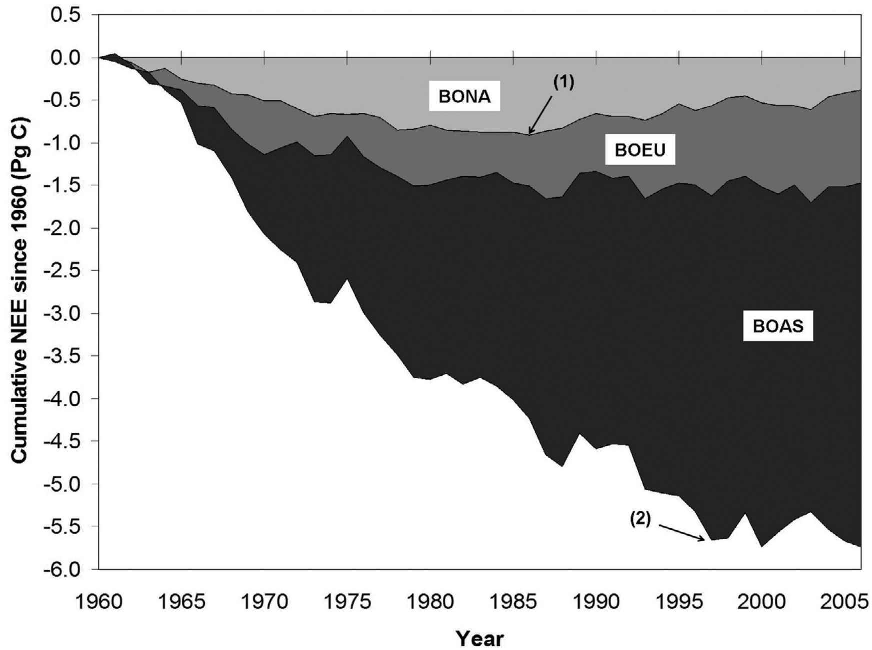

Figure 2. Estimated cumulative net uptake of atmospheric CO_2 (NEE) by boreal land regions since the latter half of the 20th century, according to the simulation experiment with all factors included (Sim7).

framework was designed to allow an analysis of the relative contribution of the different driving factors to the overall C balance of the system over the recent 10 year period. Each simulation, labeled Sim1 through Sim7, builds upon the potential vegetation data set by incorporating an additional transient data set at each successive model run. The first simulation (Sim1) was driven by nonvarying, average climate data with each year represented by mean monthly data calculated from the 1901 to 1930 time period, land cover assumed to be potential vegetation, and variable global annual atmospheric CO_2 concentrations. The Sim2 and Sim3 simulations were driven by adding spatially and temporally varying tropospheric O_3 levels and N deposition rates, respectively, with the transient [CO_2] data set. The transient climate was added on with the atmospheric chemistry data sets to drive Sim4 and all subsequent simulations. Thus, Sim1 thru Sim4 are based on undisturbed potential vegetation. In each successive model run, a new disturbance data set was imposed on potential vegetation and, along with varying atmospheric chemistry and climate, was used to drive the subsequent simulations. To distinguish the effects of wildfire, timber harvest, and agriculture, essentially three unique disturbance and land use data sets were developed for this study: one that includes only the occurrence of area burned (Sim5), a second that prescribes fire and wood harvest (Sim6), and a third that incorporates fire, timber harvest, and agricultural (crops and pastures) establishment and abandonment (Sim7). Since the transient data sets were individually added in each successive run, the effects of each on C stocks and change were determined by subtracting the results of a simulation from those of the subsequent run. Note that with this simulation framework being built in an "additive" fashion, as opposed to a full factorial analysis, any effects reported contain both the direct effects of the factor being considered plus any interactions with the factors included in the preceding simulations.

3. Results and Discussion

3.1. Diagnosis

[17] Overall, these simulations suggest a modification in trend from a pattern of steady increase in cumulative CO_2 uptake (negative NEE) by the boreal land regions over the last half of the 20th century to one of declining uptake within the last 10 to 20 years of this analysis (Figure 2). Since 1960, the boreal land regions combined show cumulative uptake up until (1) about 1986, when the BONA region begins to trend toward net CO_2 release (positive NEE); and then (2) around 1998, after which cumulative uptake begins to decline in response to an abrupt shift toward net release in BOAS. The results indicate that BONA acted as a net sink of 37 Tg C yr^{-1} from 1960 to 1986, with a change to a net source of 27 Tg C yr^{-1} from 1987 to 2006. For BOAS, TEM estimates a net C sink of 112 Tg C yr^{-1} from 1960 to 1998, with a substantial decline in net uptake to 10 Tg C yr^{-1} between 1999 and 2006. A steady sink averaging 24 Tg C yr^{-1} was estimated for BOEU terrestrial ecosystems from 1960 to 2006. Given the uncertainties and limitations of various approaches, these results are generally consistent with flux estimates from other studies of C balance in northern high-latitude land regions over the late 20th century, including assessments from inventory, process-based, and inverse models.

[18] The land-atmosphere CO_2 exchange estimated by the TEM for this study was compared with model mean and spread from the results of the TransCom 3 project, an intercomparison of atmospheric CO_2 inversion models that includes an ensemble of transport models and model variants

Table 1. A Comparison of Average Annual NEE Estimates (PgC yr^{-1}) for Different Time Periods in Boreal North America and Boreal Asia From This Study With Those From TransCom3 Atmospheric Inversion Models[a]

Time Period (Observation Network)	Boreal North America (BONA)			Boreal Asia (BOAS)		
	All T3 Models	S07 Model Subset	TEM (This Study)	All T3 Models	S07 Model Subset	TEM (This Study)
1980–1989 (23 sta)	0.145 +/− 0.336	0.344 +/− 0.469	0.012	−0.182 +/− 0.554	−0.217 +/− 0.234	−0.081
1990–1999 (23 sta)	−0.005 +/− 0.314	0.174 +/− 0.417	0.028	−0.378 +/− 0.466	−0.405 +/− 0.266	−0.089
1995–1999 (104 sta)	−0.216 +/− 0.316	−0.097 +/− 0.593	0.041	−0.208 +/− 0.326	0.066 +/− 0.233	−0.075
1995–2004 (104 sta)	−0.318 +/− 0.309	−0.209 +/− 0.586	0.019	−0.118 +/− 0.342	0.193 +/− 0.220	−0.044
2000–2004 (102 sta)	−0.295 +/− 0.354	−0.105 +/− 0.632	−0.003	−0.267 +/− 0.467	−0.033 +/− 0.093	−0.013
2003–2006 (151 sta)	−0.250 +/− 0.342	−0.104 +/− 0.595	0.045	−0.284 +/− 0.472	0.023 +/− 0.206	−0.086

[a]One comparison is with the full set of models ("All T3 Models" [*Gurney et al.*, 2008]), and the other is with a three-model subset of those identified by *Stephens et al.* [2007] as best representing observed vertical profiles of [CO_2] in the Northern Hemisphere ("S07 Model Subset"). Out of the multiple available observational networks outlined by *Gurney et al.* [2008], we are utilizing the largest network for each given averaging time period.

[*Gurney et al.*, 2004, 2002]. The TransCom 3 fluxes are based on the ensemble of models run on observation data from the different station-data networks of varying temporal extent [*Gurney et al.*, 2008]. In this comparison we consider both the full ensemble of TransCom 3 models ("All T3 Models") as well as a subset consisting of the three models (UCI, JMA and TM3) identified in the study by *Stephens et al.* [2007] as best representing observed vertical profiles of [CO_2] in the Northern Hemisphere ("S07 Model Subset"). Out of the multiple available observational networks outlined by *Gurney et al.* [2008], we are utilizing the largest network for each given averaging time period. The long-term means are sensitive to the choice of observing network and this must be considered a key caveat of the comparison. The overall C flux results from the TEM simulations are within the range of uncertainty in estimates from the TransCom 3 models over the BONA and BOAS regions for most model sets, time periods and station-data networks (Table 1). Except for the 1980 to 1999 time periods (the 23 station observation network) in BOAS, the S07 Model Subset means estimate smaller sinks or larger sources than the full set of All T3 Models. Inverse model mean estimates suggest primarily sink activity in BONA for the time periods between 1980 and 1999 followed by larger sink activity from 1995 to 2006. In contrast, TEM estimates from this study show mostly small source activity in BONA over all time periods. For BOAS, TEM estimates a general decline in sink strength over time until the 2003 to 2006 period. There is no clear trend in the All T3 Models mean estimates over time in BOAS, whereas the S07 Model Subset means suggest a switch from a large sink in earlier time periods to mostly source activity since 1995.

[19] Process-based simulation of C balance using TEM in this study generally results in smaller sink estimates than other bottom-up estimates for boreal regions in the late 20th century (Table 2). Estimates of C balance in vegetation and soils based on inventory data and process models place the estimate for the C sink in North American high-latitude forests (Canada and Alaska) between 0 and 92 Tg C yr^{-1} for the latter part of the 20th century [*Balshi et al.*, 2007; *Chen et al.*, 2000; *Kurz and Apps*, 1999], compared to estimates between 2 and 44 Tg C yr^{-1} from this study, depending on the time period bin. Inventory-based analyses indicate decreasing ecosystem C stores in Canada's managed forest

Table 2. A Comparison of Carbon Balance Estimates (TgC yr^{-1}) From This Study With Those From Other Bottom-Up (Inventory-Based and Process-Based Model Estimates) Studies for Different Boreal Regions and Time Periods

Region	Time Period	Study	Literature Estimates	This Study
Alaska	1980–1989	*Balshi et al.* [2007][a]	5 to 12	0
	1990–1999	*Balshi et al.* [2007][a]	0 to 9	−4
Canada	1970–1989	*Kurz and Apps* [1999][b]	52	44
		Balshi et al. [2007][a]	12 to 58	44
	1980–1996	*Chen et al.* [2000][a]	26 to 80	6
		Balshi et al. [2007][a]	−1 to 57	6
	1990–1999	*Liski et al.* [2003][c]	100	41[d]
	1995–1999	*Myneni et al.* [2001][c]	73	67[d]
		Balshi et al. [2007][a]	0 to 80	11
Finland	1990–1999	*Liski et al.* [2002][b]	7	2
Norway	1990–1999	*Liski et al.* [2002][b]	3	2
Russia	1961–1998	*Shvidenko and Nilsson* [2002][c]	210	171[d]
		Shvidenko and Nilsson [2003][b]	322	94
		Balshi et al. [2007][a]	68 to 220	94
	1981–1999	*Beer et al.* [2006][a]	171	89
	1990–1999	*Liski et al.* [2003][c]	430	200[d]
Sweden	1990–1999	*Liski et al.* [2002][b]	15	−3

[a]Process-based model estimate of total C balance.
[b]Inventory-based estimate of total (vegetation and soils) C balance.
[c]Inventory-based estimate of C sink in woody biomass only.
[d]Estimate of C balance in vegetation only (this study).

Table 3. The Quantitative Effects of the Controlling Factors Considered Among the Various Simulations in This Study on Average Annual Net Ecosystem Exchange (NEE; Tg C yr^{-1}) for the Arctic Tundra and Boreal Forest Ecozones in the Boreal North America (BONA), Boreal Europe (BOEU), and Boreal Asia (BOAS) Land Regions, Over the 1997 to 2006 Analysis Period[a]

Effect	BONA			BOEU			BOAS		
	Arctic Tundra	Boreal Forest	All	Arctic Tundra	Boreal Forest	All	Arctic Tundra	Boreal Forest	All
CO_2 (Sim1)	−25.0	−20.5	−46.9	−2.1	−13.8	−23.7	−27.3	−96.5	−128.4
O_3 (Sim2 – Sim1)	0.0	0.2	0.2	0.0	2.6	3.8	0.3	6.0	6.7
N Dep. (Sim3 – Sim2)	−0.7	−0.8	−2.3	−0.2	−1.4	−28.1	−1.6	−8.9	−16.7
Climate (Sim4 – Sim3)	22.3	29.3	49.4	3.2	23.0	19.9	5.0	30.3	25.1
Fire (Sim5 – Sim4)	3.1	20.4	23.1	0.0	−2.6	−4.7	−3.5	74.5	73.1
Harvest (Sim6 – Sim5)	0.2	0.1	−0.8	0.0	2.7	1.6	0.3	−4.0	−6.1
Agriculture (Sim7 – Sim6)	−0.3	1.7	1.3	0.0	2.1	9.7	−0.1	7.8	3.2
TOTAL (Sim7)	−0.3	30.3	23.9	0.9	12.7	−21.5	−27.0	9.2	−43.1

[a]The "All Ecozones" column presents the totals for all land area in each region, including the other ecozones (i.e., temperate forest and woodlands/grasslands) in addition to Arctic tundra and boreal forest.

area since the 1980s in response to increases in disturbance [*Kurz and Apps*, 1999]. Inventory-based assessments suggest a net uptake of atmospheric CO_2 between 93 and 347 Tg C yr^{-1} in Eurasian forests over the late 20th century [*Beer et al.*, 2006; *Goodale et al.*, 2002; *Liski et al.*, 2002, 2003; *Myneni et al.*, 2001; *Shvidenko and Nilsson*, 2002, 2003], with much of this estimated sink attributed to Scandinavia and European Russia. This study has a lower estimate for the Eurasian forest C sink between 90 and 95 Tg C yr^{-1}.

[20] The sum of the literature-based estimates in Table 2 for the late 20th century across Alaska, Canada, Scandinavia and Russia provides a range of increase in the total C stocks of northern high-latitude vegetation and soils of between 93 to 439 Tg C yr^{-1} in the late 20th century. In comparison, our simulations estimate a 141 Tg C yr^{-1} sink over the northern high-latitude land region from 1960 to 1999, which includes 349 Tg C yr^{-1} of net ecosystem production (NEP) balanced by 177 Tg C yr^{-1} emitted in fires and 31 Tg C yr^{-1} released through decay of C in the product pools. Given the more comparable NEP estimates, our overall sink estimate may be at the low end of the range in other estimates in part because of differences in how disturbance and land use related fluxes are, or are not, treated in these other studies. Additionally, when the C balance of only vegetation stocks from our study is compared with inventory-based estimates of woody biomass [i.e., *Liski et al.*, 2003; *Myneni et al.*, 2001; *Shvidenko and Nilsson*, 2002] (see Table 2), there is greater convergence of results, which suggests that much of the uncertainty lies in the treatment of soil C fluxes. While many of the inventory-based studies estimate net C storage in soils [*Liski et al.*, 2002; *Shvidenko and Nilsson*, 2003], our study suggests net C loss from the soils of the northern high-latitude land regions in recent decades through decomposition and fire emissions in response to climate and disturbance effects.

3.2. Attribution

[21] Over the most recent 10 year period of the analysis (1997 to 2006), all ecozones combined show a 24 Tg C yr^{-1} source in BONA counteracted by sinks of 22 Tg C yr^{-1} and 43 Tg C yr^{-1} from BOEU and BOAS, respectively (Table 3). Boreal forests across the regions act as a CO_2 source (52 Tg C yr^{-1}), which overwhelms the corresponding net sink (26 Tg C yr^{-1}) in tundra ecosystems. The simulation of individual effects suggests that the net exchange of CO_2 from the boreal land regions to the atmosphere is driven primarily by the effects of climate and fire on NEE (94 and 92 Tg C yr^{-1}, respectively), which offset uptake as a result of the fertilization effects of CO_2 and N deposition (199 and 47 Tg C yr^{-1}, respectively). Our simulations also indicate that the land sinks caused by CO_2 fertilization and atmospheric N deposition increased in strength over the latter half of the 20th century (Figure 3). Increasing atmospheric [CO_2] is responsible for most of the uptake in these land regions, and N deposition has a significant impact on temperate forests in BOEU. The effect of CO_2 fertilization in our simulations is largely constrained by N dynamics in the model [*McGuire et al.*, 1997; *Sokolov et al.*, 2008], particularly in northern high-latitude regions, and is generally less in magnitude than estimated by other global process-based models [*McGuire et al.*, 2001]. The consideration of the effects of N limitation on C uptake, as with this study, tends to attenuate ecosystem responses and produce smaller sink estimates [*Jain et al.*, 2009; *Thornton et al.*, 2007]. Other studies have also shown that CO_2 fertilization effects play a significant role in the C sink of high-latitude regions [*Balshi et al.*, 2007; *Beer et al.*, 2006], but our results suggest that these effects are largely offset by the source effects of climate and disturbance in the last decade of analysis.

[22] The climate-induced CO_2 release from land to the atmosphere (positive NEE) across all regional ecozones reflects an increase in mean annual surface air temperature of 1°C experienced by the boreal land regions (BONA, BOEU and BOAS) in the recent 10 year analysis period (1997–2006) as compared to the long-term mean from a reference period (1961–1990). The NEE response to warming is a result of positive climate effects on both NPP and HR across the regional ecozones since the 1960s (Figure 4). In general, the effect has been stronger on HR than NPP, which accounts for the increasingly positive (source) climate effect on NEE shown for the northern high-latitude terrestrial ecosystems. In tundra ecosystems, the increase in NPP simulated here is corroborated by observations, described in other studies, of enhanced productivity in the Arctic due to increased CO_2 uptake [*Oechel et al.*, 2000], longer growing seasons [*Goetz et al.*, 2005; *Piao et al.*, 2007], and the expansion of woody vegetation [*Sturm et al.*, 2001]. However,

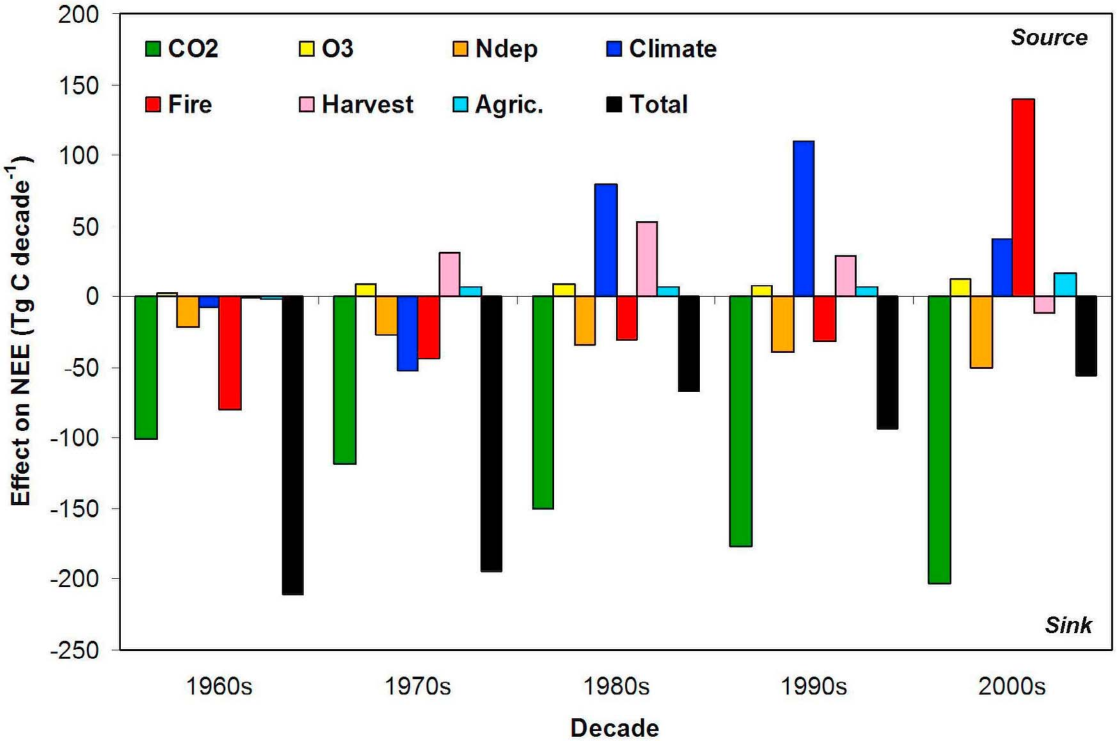

Figure 3. Total and individual average annual effects (Tg C yr^{-1}) of temporal variability in atmospheric [CO_2], tropospheric O_3 levels, N deposition rates, climate, fire, forest harvest, and agricultural establishment and abandonment on NEE for each decade since the 1960s across the northern high-latitude study area (the BONA, BOEU, and BOAS regions combined).

the effects of climate variability show that increased HR, responding to warmer temperatures, outpaced this increase in NPP and weakened the tundra CO_2 sink.

[23] The simulations show a similar climate effect on the changes in the vegetation production versus soil decomposition balance in boreal forests, with strong increases in both NPP and HR over the late 20th century. While these simulations and other studies [*Piao et al.*, 2007; *Qian et al.*, 2010] suggest climate-driven increases in boreal forest vegetation productivity, some studies based on satellite observations suggest a declining trend in photosynthetic CO_2 uptake in these ecosystems across the northern high latitudes [*Goetz et al.*, 2007]. There is also no clear consensus from the scientific literature on the expected long-term response of

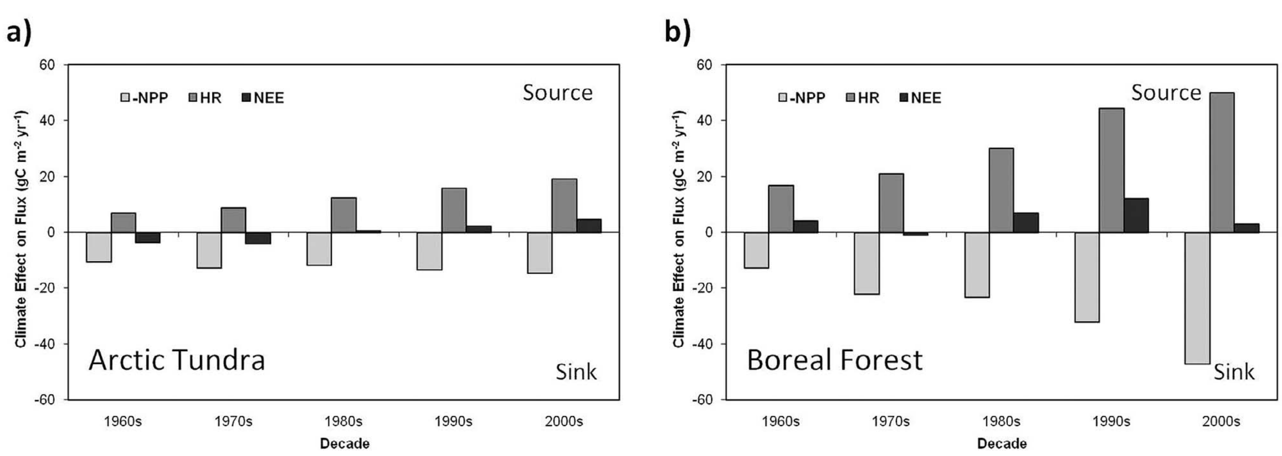

Figure 4. The area-weighted climate effects (g C m^{-2} yr^{-1}) on simulated NEE and its component fluxes (−NPP and HR) for each decade since the 1960s, shown for the (a) Arctic tundra and (b) boreal forest ecozones across the boreal land regions combined (boreal North America, boreal Europe, and boreal Asia). Note that net primary productivity is depicted with an opposite sign convention, meaning that a −NPP represents a sink effect.

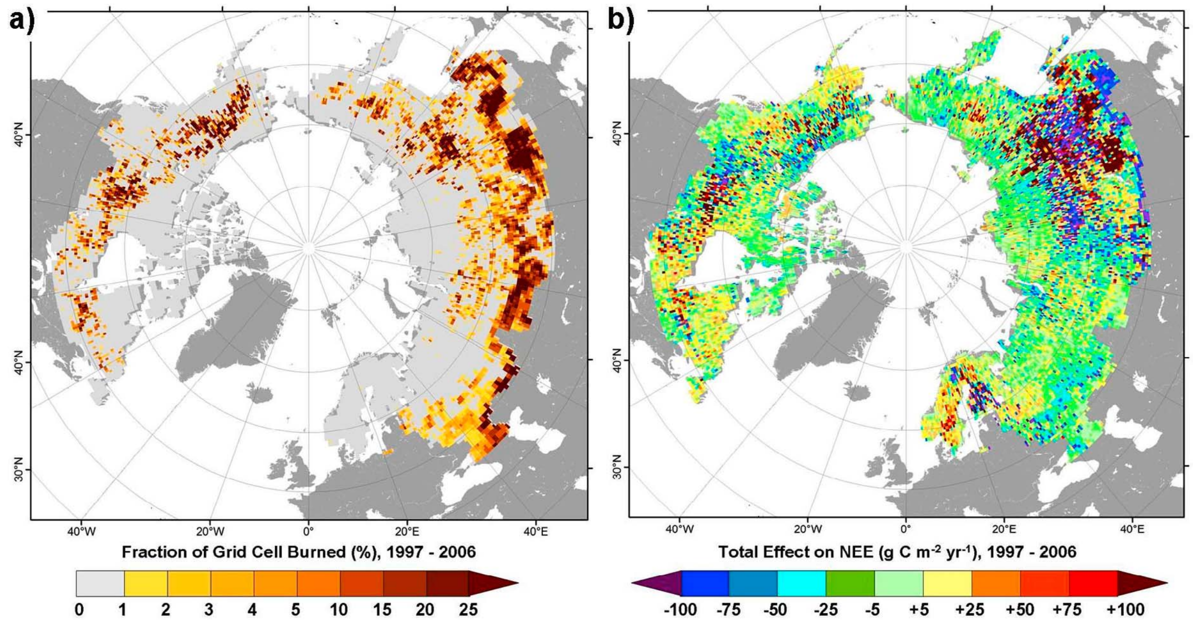

Figure 5. The spatial pattern of the (a) total fraction of grid cell area burned and (b) average annual effect (gC m^{-2} yr^{-1}) of all controlling factors on NEE across the boreal land regions over the 1997 to 2006 time period.

SOM decomposition in boreal forest soils to warming. Experimental studies in northern temperate forests have shown significant increases in soil CO_2 efflux with soil warming [*Peterjohn et al.*, 1994; *Rustad and Fernandez*, 1998], while similar experiments in boreal region plantations show no temperature effect on HR after 2 to 3 years [*Strömgren and Linder*, 2002; *Bronson et al.*, 2008]. The modeling study by *Bond-Lamberty et al.* [2007] suggests that changes in climate did not have a significant impact on the long-term C balance of a boreal forest region in Canada, whereas measurements in the same region reported by *Goulden et al.* [1998] show significant increase in the decomposition of SOM following permafrost thaw.

[24] The increases in HR in our simulations are a function of greater microbial activity in response to warmer temperatures, as well as a result of more soil C available for decomposition from increasing active layer depth (ALD) tied to permafrost thaw. Our simulations show a change in the temporal trends of increasing ALD for both tundra and boreal forest ecozones since the 1960s, which follows closely with the increases in surface air temperature over the region during the same time period. From 1900 to 1965, the mean annual maximum ALD as simulated by TEM increases at a rate of 0.44 mm yr^{-1} in tundra and 0.80 mm yr^{-1} in boreal forest. The rate of ALD increase more than doubles after 1965 in both tundra and boreal forest, to 1.28 mm yr^{-1} and 1.61 mm yr^{-1}, respectively. All reported trends are statistically significant ($p < 0.001$). Field-based measurements of ALD have been collected at sites spanning the pan-Arctic over the last 10–15 years as part of the Circumpolar Active Layer Monitoring (CALM) program [*Brown et al.*, 2000]. These data show large interannual variability in ALD at the site level [e.g., *Smith et al.*, 2009], and the decadal-scale trends are highly variable by region. Increasing trends in ALD have been observed for several sites in Scandinavia [e.g., *Åkerman and Johansson*, 2008] and Russia [e.g., *Mazhitova et al.*, 2008]. In North America, ALD has been relatively stable in high Arctic areas [e.g., *Smith et al.*, 2009] with increasing trends restricted primarily to sites in the Alaskan interior [*Viereck et al.*, 2008].

[25] Studies suggest that the microbial decomposition of previously frozen organic matter can overcome uptake from increased vegetation productivity to alter the C balance in tundra ecosystems over decadal time scales [*Oechel et al.*, 1993; *Schuur et al.*, 2009; *Schaefer et al.*, 2011]. The impact of these ALD dynamics on simulated C release from soils depends on model assumptions about the distribution of C stocks with depth (see Text S1). The recent study by *Tarnocai et al.* [2009] suggests that high-latitude soil and permafrost C stocks are much greater than previously thought, and experimental evidence in the study by *Schuur et al.* [2009] demonstrates the potential for substantial C release from thawing permafrost. Considering permafrost carbon in simulation modeling can lead to qualitatively different responses of the pan-Arctic carbon balance to climate warming [*Schaefer et al.*, 2011], and exploring these key issues in more detail with the TEM model is the subject of ongoing research.

[26] The large effect of fire on NEE is a result of extensive wildfires occurring across the boreal land regions between 1997 and 2006, in which a total area of 87.6 M ha burned. The majority of this burn area (64.4 M ha) occurred in boreal Asia where, combined with large C stores in Siberian boreal spruce and larch forests, fires result in an estimated CO_2 release of 255 Tg C yr^{-1}. Fire emissions from boreal North America add an additional release of 51 Tg C yr^{-1} as CO_2 from fires that burned 23.2 M ha, impacting boreal forests as well as some shrub tundra regions along ecozone transition boundaries. The net effect of this large CO_2

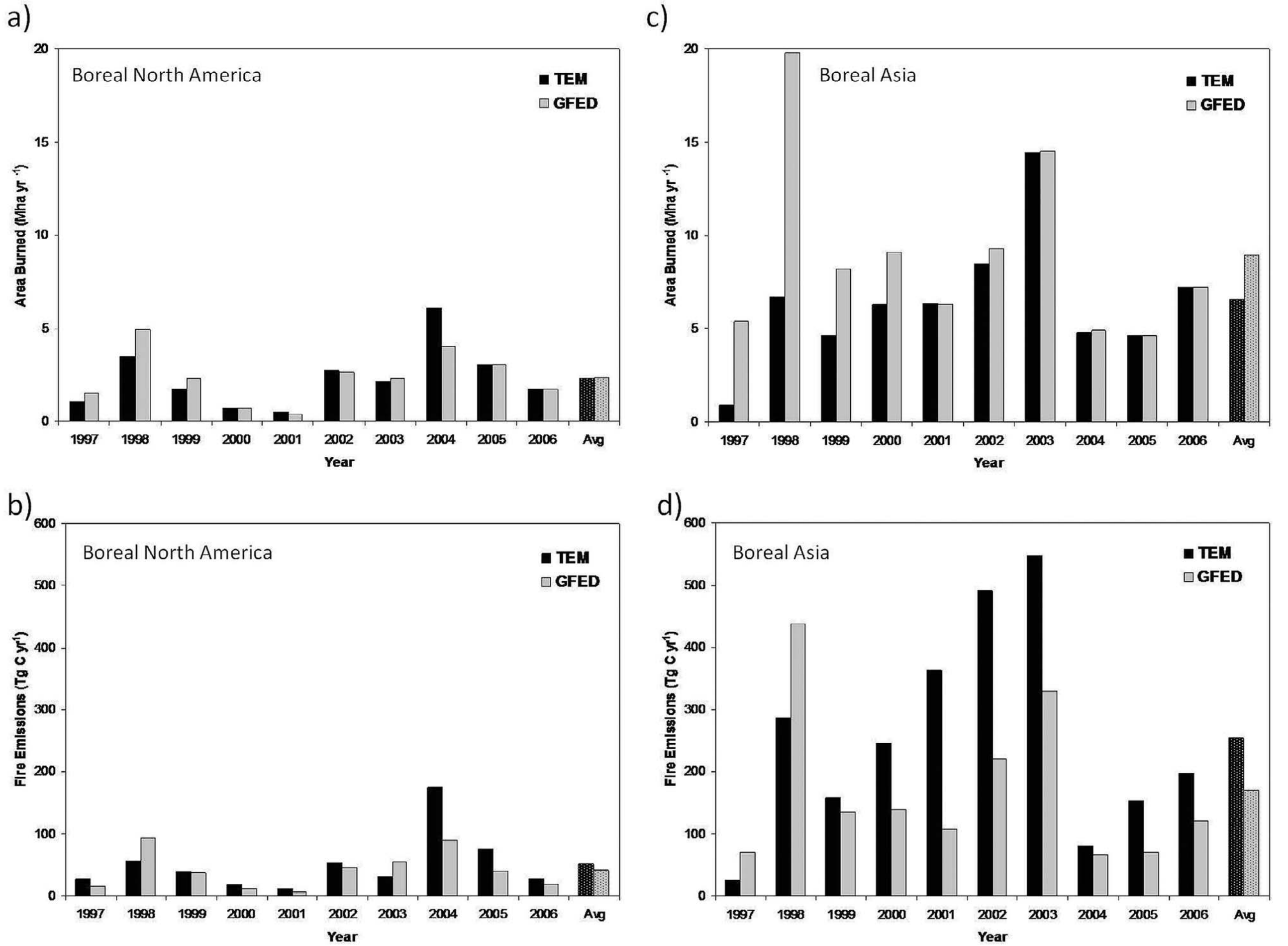

Figure 6. Comparison of estimates of both (a, c) area burned and (b, d) fire emissions over the 1997–2006 time period between the Global Fire Emissions Database (GFEDv2) and this study (TEM). Annual fire emissions (Tg C yr^{-1}) over the 1997–2006 time period are shown for boreal North America (Figure 6c) and boreal Asia (Figure 6d), where total emissions estimated by TEM are separated into the release contributed by conversion of vegetation C and soil C in fires.

release from fire emissions can be seen where areas of high fire activity are similar to areas with large positive (source) NEE across the boreal land regions (Figure 5). The fire data set used in this study show increases in annual area burned for the region as a whole during years of the 1997 to 2006 time period, compared with earlier decades. Annual area burned in the BONA region shows a significant increasing trend ($p < 0.01$) since the beginning of the historical fire record, with an average of 21 M ha burned per decade since the 1980s. In the BOAS region, average annual area burned between 1997 and 2006 from to the historical data set is 43% greater than that of previous years since 1960, according to the back-casted data developed by *Balshi et al.* [2007]. While these data suggest a change in fire regime in BOAS in recent years, a more solid conclusion is difficult to attain given the short duration of the historical fire record and uncertainty about reports of area burned in Russia for previous years [*Conard et al.*, 2002; *Shvidenko and Nilsson*, 2000]. However, an unusually high frequency of "extreme fire years" have been observed in the past decade [*Soja et al.*, 2007] relative to what is known about previous fire history in Siberian boreal forests [*McGuire et al.*, 2002; *Shvidenko and Nilsson*, 2000]. According to our results, fire at lower levels of area burned in the 20th century created a net sink effect at the northern high-latitude regional scale (Figure 5). The increase in area burned over the whole study area results in the large source effect from fire in the most recent years of analysis.

[27] The TEM estimate of 306 Tg C yr^{-1} emitted from fires for these two regions over the 1997 to 2006 time period is larger than the 212 TgC yr^{-1} estimate from the Global Fire Emissions Database, version 2 [*Randerson et al.*, 2006] (Figure 6). With similar burn areas from 1997 to 2006 between the two data sets, the differences in fire emission estimates are likely due to differences in modeled C stocks and the parameters used to estimate C fractions consumed, emphasizing the sensitivity of emissions estimates to the simulation of biomass "fuel loads" in vegetation and soils, as well as to other environmental factors in boreal forest ecosystems [*French et al.*, 2004; *Yi et al.*, 2009]. In our simulations, the majority (58% in BONA and 64% in BOAS) of CO_2 emissions released in fires during the 1997

to 2006 time period were from consumption of dead organic matter, which is consistent with other studies of aboveground live and surface/belowground dead organic matter fractions consumed in boreal forest fires [*French et al.*, 2000; *Kasischke and Bruhwiler*, 2002; *Wirth et al.*, 2002]. With respect to uncertainty in the impacts of disturbance on NEE, it is also important to note that the data sets used to drive the model simulations presented here do not include any data on insect disturbance, which could provide a significant additional C source in peak outbreak years on a regional scale with a magnitude comparable to that of fires [*Kurz et al.*, 2008b]. Like fire, insect outbreaks are expected to increase in frequency, severity and extent over boreal forest regions in response to future climate warming [*Juday et al.*, 2005].

[28] The overall system behavior found in the simulations presented here diverges in some important ways from both the conceptual hypotheses and other model results that suggest increased carbon storage in high-latitude ecosystems in a warmer, CO_2-enriched world. We suspect that much of this divergence can be attributed to particular updates to the model formulation in this recent version of TEM (see Text S1), as well as to the inclusion of the major controlling factors on carbon cycling as model driving data (i.e., atmospheric chemistry, climate and disturbance). For example, simulated carbon exchange in this study differs markedly even from that of the recent study by *Balshi et al.* [2007], who used a previous version of TEM to estimate fire emissions and carbon balance across the pan-Arctic (Table 2). We found that a conceptual change in the model involving the effects of active layer depth on the availability of soil organic carbon for decomposition and combustion (see Text S1) strongly affects the estimates of regional carbon exchange. This study has also incorporated the impacts of forest harvest and land use in addition to the influence of fire that was considered in the *Balshi et al.* [2007] study. The impacts of disturbance of all kinds are important not only for the short-term transfer of carbon in the system, but also with respect to the legacy effects on stand age distribution and its influence on regional-scale primary productivity and energy exchange [*Chen et al.*, 2002; *Euskirchen et al.*, 2010]. Overall, this study highlights examples of key mechanisms controlling carbon-climate feedbacks in high-latitude systems that are not adequately represented in current generation earth system models.

4. Conclusion

[29] This study addresses the question of the response of contemporary northern high-latitude terrestrial carbon dynamics to recent changes in atmospheric chemistry, climate and disturbance using a process-based modeling approach. Our results suggest a substantial weakening of the strength of the land-based sink for atmospheric CO_2 across the region in a recent 10 year time period. The simulations that we conducted show CO_2 release from warming-induced SOM decomposition and combustion in boreal forest fires is outpacing increases in uptake responding to temperature increases and atmospheric CO_2 and N fertilization. While multiple lines of evidence have begun to emerge on the impacts of various individual feedback mechanisms between climate and high-latitude ecosystem processes, our study emphasizes the importance of considering all major controlling factors in a comprehensive, integrated analysis of the response of the land-based CO_2 sink.

[30] The changes to the strength of the northern high-latitude terrestrial CO_2 sink suggested by this analysis have important consequences for global climate change research and policy. Attempts have been made to identify anthropogenic emission targets that, given the current rates of sequestration in terrestrial ecosystems, would result in atmospheric CO_2 concentrations stabilized at levels that mitigate the effects of future climate change. However, these rates of sequestration are neither permanent nor fixed; globally, there is evidence suggesting that CO_2 uptake by biological processes may saturate in coming decades [*Canadell et al.*, 2007a, 2007b]. Combined with the emissions component from increasing disturbance, this scenario could eventually cause terrestrial ecosystems to shift from a sink to a net carbon source. In considering the major controlling factors on the land-atmosphere exchange of CO_2, our results suggest that this process may already be underway in recent decades across the northern high latitudes. The disappearance of this regional CO_2 sink would reduce the overall future global terrestrial sink, effectively accelerating the buildup of anthropogenic CO_2 in the atmosphere. Efforts to establish targets for reduced rates of anthropogenic emissions should take into account the potential for near-term disappearance of the northern high-latitude terrestrial CO_2 sink.

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