Global Change Biology

Global Change Biology (2013) **19**, 604–620, doi: 10.1111/gcb.12041

The response of soil organic carbon of a rich fen peatland in interior Alaska to projected climate change

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Abstract

It is important to understand the fate of carbon in boreal peatland soils in response to climate change because a substantial change in release of this carbon as CO_2 and CH_4 could influence the climate system. The goal of this research was to synthesize the results of a field water table manipulation experiment conducted in a boreal rich fen into a process-based model to understand how soil organic carbon (SOC) of the rich fen might respond to projected climate change. This model, the peatland version of the dynamic organic soil Terrestrial Ecosystem Model (peatland DOS-TEM), was calibrated with data collected during 2005–2011 from the control treatment of a boreal rich fen in the Alaska Peatland Experiment (APEX). The performance of the model was validated with the experimental data measured from the raised and lowered water-table treatments of APEX during the same period. The model was then applied to simulate future SOC dynamics of the rich fen control site under various CO_2 emission scenarios. The results across these emissions scenarios suggest that the rate of SOC sequestration in the rich fen will increase between year 2012 and 2061 because the effects of warming increase heterotrophic respiration less than they increase carbon inputs via production. However, after 2061, the rate of SOC sequestration will be weakened and, as a result, the rich fen will likely become a carbon source to the atmosphere between 2062 and 2099. During this period, the effects of projected warming increase respiration so that it is greater than carbon inputs via production. Although changes in precipitation alone had relatively little effect on the dynamics of SOC, changes in precipitation did interact with warming to influence SOC dynamics for some climate scenarios.

Keywords: boreal, carbon, climate change, fen, methane, model, peatland, soil CO_2 flux

Received 7 June 2012; revised version received 10 September 2012 and accepted 14 September 2012

Introduction

Peatlands in the boreal region cover 3.4×10^6 km^2, which is approximately 3% of the world's land surface area or 15% of the northern high latitude land surface area (Gorham, 1991; Rydin & Jeglum, 2006; Lai, 2009). A large amount of soil organic carbon (SOC) (270–370 Gt; Turunen *et al.*, 2002) has accumulated in boreal peatland ecosystems during the Holocene (Zoltai, 1995). Several factors, including low temperature, high soil moisture content, and low wildfire frequency have been responsible for the long-term storage of SOC in peatlands (Hobbie *et al.*, 2000; Grosse *et al.*, 2011). These factors, which are changing in northern high latitudes and are expected to continue to change in the future (McGuire *et al.*, 2007), have consequences for carbon dynamics of boreal peatlands. For example, warming along with the changes in distribution and quantity of annual precipitation may significantly change soil hydrology, thermal, and permafrost dynamics to influence SOC dynamics (Zhuang *et al.*, 2003; Carrasco *et al.*, 2006; Fan *et al.*, 2008, 2011). Because of the large storage of SOC in boreal peatlands, altered SOC dynamics may have implications for atmospheric concentrations of CO_2 and CH_4 in the atmosphere. Thus, it is critical to understand the fate of boreal peatland SOC in response to climate change (Waddington & Roulet, 2000; Bauer & Vitt, 2011; Frolking *et al.*, 2011).

In boreal peatlands, the SOC horizons above the mineral horizon are characterized by low bulk density (mean bulk density of 0.122 g cm^{-3}; Gorham, 1991; Turunen, 2003), high porosity (Yi *et al.*, 2009a), and high spatial and temporal variability in soil thermal and hydrological properties (O'Donnell *et al.*, 2009). Also, the mean thickness of SOC horizons in boreal peatlands typically ranges from 1.5 to 2.5 m (Gorham,

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1991; Turunen, 2003). Due to these unique characteristics, the physical properties of boreal SOC horizons play a critical role in regulating soil temperature and moisture dynamics as well as permafrost dynamics and net primary productivity (NPP), all of which, in turn, affect the dynamics of SOC and its physical properties (Euskirchen *et al.*, 2009; Yi *et al.*, 2009b, 2010).

An important, but uncertain response of boreal peatlands to climate change is the fate of SOC, particularly the degree to which soil CO_2 and CH_4 exchange with the atmosphere is affected by climate change. The input of carbon to SOC horizons in peatlands depends on the response of NPP to changes in climate and atmospheric chemistry. The atmospheric loss of SOC in peatlands is controlled by aerobic and anaerobic decomposition, combustion by wildfire, and by exports in dissolved and particulate phases. Aerobic decomposition, which generally occurs above the water table where oxygen supply is not limited, produces CO_2. Anaerobic decomposition, which generally occurs below the water table where oxygen supply is limited (Moore & Dalva, 1997), produces CH_4 (Ramaswamy *et al.*, 2001) and possibly CO_2 under fermenting conditions (Blodau & Moore, 2003) and through methanogenesis, denitrification, sulfate reduction, iron reduction, manganese reduction, and other mechanisms (Blodau & Moore, 2003; Keller & Bridgham, 2007). Climate change may affect the loss of SOC through changes in soil temperature and moisture that influence the rate or mechanism of decomposition.

After CO_2 is produced in the unsaturated and saturated zones, it will be released to the atmosphere exclusively through molecular diffusion. Unlike CO_2, CH_4 produced in the saturated soil zone can also be oxidized in the unsaturated soil zone before being released to the atmosphere (e.g. Singh *et al.*, 2009). Therefore, the transport pathways of CH_4 in soils are essential to the release of CH_4 from soil to the atmosphere. CH_4 can be transported through the tissues of some vascular plant species (e.g. Sutton-Grier & Megonigal, 2011), episodic or steady state ebullition (e.g. Fechner-Levy & Hemond, 1996; Baird *et al.*, 2004), and diffusion (e.g. Clymo & Bryant, 2008). As a result, the production, transport, and emission of CH_4 is controlled by various complex interactions among soil physical (e.g. porosity), biological (e.g. vegetation species and root distribution), and hydrological (e.g. water table) properties.

In this study, we synthesized the results of a field water table manipulation experiment conducted in a boreal rich fen into a process-based model to understand how SOC and soil CO_2 and CH_4 fluxes might respond to projected climate change. Our approach was to calibrate the model based on data from the control treatment of the manipulation experiment, and to validate the model based on the data from two experimental treatments, including raised and lowered water table manipulations. Because we measured gas fluxes for several years, we also captured a large amount of interannual variation across all treatments, including a dry year and a 100-year flood for the region. We conducted a scaling study to evaluate whether or not the model could be driven by monthly instead of daily input climate data. The model was then used to simulate SOC dynamics (i.e. C inputs into the soil, CO_2 and CH_4 exchange with the atmosphere, and changes in soil C stocks) of the control treatment under various CO_2 emission scenarios (high, midrange, and low emissions). We analyzed the results of these simulations to evaluate how increases in atmospheric CO_2, warming, and changes in precipitation influence SOC dynamics in the rich fen.

Materials and methods

Site description

The data used to develop and validate the model in this study were obtained from the rich fen peatland of the Alaska Peatland Experiment (APEX; 64.82°N, 147.87°W), which is located near the Bonanza Creek Experimental Forest southwest of Fairbanks, Alaska. Radiocarbon (^{14}C) dating for soil core taken from APEX suggests approximately 2000 years of age at a depth of 90 cm near the base of the peat (J.W. Harden, data not shown). The site is treeless and mainly overlain by *Sphagnum* moss and emergent vascular species (Turetsky *et al.*, 2008; Chivers *et al.*, 2009). The peat thickness above the mineral soil is approximately 1 m. Three water table treatments were established in this ecosystem in 2004 and surrounded by boardwalks. These plots received one of three water table treatments in 2005, including a control treatment (no manipulations), a lowered treatment (created by passive drainage through trenches dug into the peat that were located outside of the treatment), and a raised treatment (created by pumping surface water into the plot through a nearby surface well). Water table position, surface soil moisture, and soil temperature at multiple depths were measured continuously in each plot from 2005 to 2011. Soil CO_2 and CH_4 fluxes were measured by placing static chambers on collars permanently installed in the peat to a depth of about 5 cm and measuring changes in headspace concentrations. Gas fluxes were measured approximately every 2 weeks from late May to September. More information on CH_4 and CO_2 flux methods can be found in Turetsky *et al.* (2008) and Chivers *et al.* (2009), respectively.

Model description

In this study, we developed the peatland version of the dynamic organic soil Terrestrial Ecosystem Model (peatland DOS-TEM). DOS-TEM has been well documented and used to investigate the dynamics of boreal forest SOC at various temporal and spatial scales (Yi *et al.*, 2009b, 2010; Yuan *et al.*, 2012). In the DOS-TEM, the SOC is separated into three horizons: fibric, amorphous, and mineral. The soil organic structure consists of a maximum of three fibrous organic layers and 10 amorphous organic layers. The mineral horizon, from top to bottom, consists of four layers with thickness of 10 cm, three layers with thickness of 20 cm, three layers with thickness of 30 cm, one layer with thickness of 50 cm, and one layer with thickness of 100 cm. Thus, the thickness of the mineral soil is 3.4 m in total. Below mineral soil is a rock horizon that consists of five layers. The total thickness of mineral and rock horizons is approximately 50 m (Yi *et al.*, 2009b). Within each of these horizons, there are several layers for which SOC is explicitly tracked based on inputs and controls appropriate to each layer. There are five modules in peatland DOS-TEM that affect SOC dynamics in the model: (1) the environmental module that simulates the soil temperature, moisture, and water table using the input climate datasets (e.g. air temperature, precipitation); (2) the ecological module that simulates the carbon and nitrogen dynamics of both vegetation and soil; (3) the dynamic organic soil module that simulates the structure of SOC above the mineral soil based on relationships between SOC thickness and SOC mass; (4) the disturbance module that simulates the impact of wildfire on SOC stocks; and (5) the peatland module that simulates soil anaerobic CH_4 and CO_2 production and the dynamics of transport pathways in the soil. The dynamics of the peatland module are affected by information received from the environmental, ecological, and dynamic organic soil modules, and the dynamics of the peatland module influence the ecological and dynamic organic soil modules. The environmental module is described in detail in Yi *et al.* (2009b) and the ecological and dynamic organic soil modules are described in detail by Yi *et al.* (2010). Please see the supporting materials for brief descriptions of these modules as well as a detailed description of the peatland module. Because we did not implement the effect of fire on peatland dynamics in this study, we do not describe the disturbance module in the supporting materials; information on the disturbance module can be found in Yi *et al.* (2010) and Yuan *et al.* (2012). In the following paragraphs we provide an overview of the peatland module.

In the peatland module (Fig. 1), microbial decomposition of SOC in peatlands/wetlands is divided into aerobic and anaerobic decomposition. Aerobic decomposition, i.e. heterotrophic respiration, is calculated by the ecological module, and is assumed to exclusively occur in the unsaturated zone (above water table); CO_2 is the only terminal product of aerobic decomposition. Anaerobic decomposition occurs exclusively in the saturated zone (below the water table) and both CH_4 and CO_2 are the terminal products of anaerobic decomposition (Fig. 1).

The production of CH_4 in the model (anaerobic decomposition of SOC) is a function of a decomposition rate limiting parameter, SOC mass, and soil temperature (Q_{10} of 2.0) in each SOC layer. The anaerobic decomposition rate limiting parameters of fibric, amorphous, and mineral SOC are not known and were calibrated with field observations as discussed later. Once CH_4 is produced in the soil, its transport is controlled by various mechanisms (Fig. 1). Diffusion transport of CH_4 is simulated based on the Fick's Law and is a function of CH_4 concentration, soil porosity, soil moisture, and soil temperature (Pingintha *et al.*, 2010). Plant-mediated transport through the roots of vascular plant species is assumed to be a function of CH_4 concentration, root distribution, leaf area index, and an empirical parameter linked to the dominant plant functional type (Walter & Heimann, 2000). Ebullition is modeled so that bubbles are formed when the CH_4 concentration in the soil water is greater than a certain threshold value (i.e. saturation concentration of CH_4) that is a function of soil temperature (Yamamoto *et al.*, 1976; Wania *et al.*, 2010). The total CO_2 release from the soil is calculated as the sum of CO_2 produced from decomposition of SOC under aerobic conditions, CO_2 produced during the microbial oxidation of CH_4 in the oxic zone, and the anaerobic production of CO_2. The aerobic production of CO_2 in the model (aerobic decomposition) is a function of soil temperature and moisture, a decomposition rate-limiting parameter, and SOC mass in each SOC layer. The same Q_{10} function (Q_{10} of 2.0) was used to simulate the impacts of soil temperature

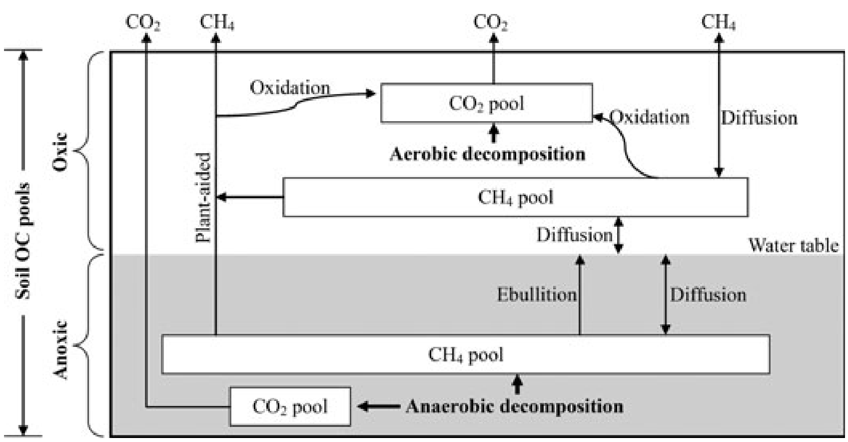

Fig. 1 Schematic of the peatland organic carbon module in peatland DOS-TEM.

on the production of CO_2. The impact of soil moisture on production of CO_2 is calculated using the moisture response curves described by Yi *et al.* (2010) with the optimal volumetric moisture content for decomposition set to 50% saturation. The aerobic decomposition rate limiting parameters were also calibrated with observations. During the transport of CH_4 in the soil-water system, a proportion of CH_4 can be oxidized before being released to the atmosphere. The oxidation of CH_4 in the unsaturated soil layers is assumed to follow Michaelis-Menten kinetics and is strongly controlled by soil temperature. It is assumed that 50% of CH_4 transported by plants is oxidized in the rhizosphere before being released into the atmosphere (Walter & Heimann, 2000). The anaerobic production of CO_2 in the model is calculated based on the aerobic production of CO_2. Many laboratory incubation studies (e.g. Updegraff *et al.*, 1995; Bergman *et al.*, 1999; Glatzel *et al.*, 2004; Kane *et al.*, 2012; Lee *et al.*, 2012) indicate that aerobic: anaerobic CO_2 production ratios in high-latitude peatland ecosystems range between 0.28 : 1 and 5 : 1. Therefore, we assumed that the ratio of aerobic CO_2 to anaerobic decomposition is two for an aerobic CO_2 flux calculated for simulated soil temperature and optimum soil moisture of 50% saturation.

Model calibration

The observations obtained from the control treatment of the APEX fen water manipulation experiment were used to calibrate peatland DOS-TEM. Since there are six unknown parameters in the model (i.e. decomposition rate-limiting parameters of fibric, amorphous, and mineral soil horizons under aerobic and anaerobic conditions), the coupled peatland and DOS-TEM model must be calibrated to estimate these unknown parameters. The objective of calibration is to match the simulated important ecosystem variables with the values of observed variables in the control treatment of APEX. This was done by tuning the decomposition rate-limiting parameters for the fibric, amorphous, and mineral soil horizons under aerobic (K_{CO2}) and anaerobic conditions (K_{CH4}) (see Eqns (3) and (9) in the supporting materials). The target values of the ecosystem variables that were used during the calibration process were either measured on site in the fen control plot of APEX or were obtained from similar ecosystems (Table 1). The calibration procedure we used for peatland DOS-TEM is similar to that described by Clein *et al.* (2002), but with modifications appropriate to this modeling framework.

During the calibration, the model was first run to reach equilibrium in year 1000 using mean 1901–1930 monthly climate data for air temperature, precipitation, atmospheric CO_2 concentration, vapor pressure, and solar radiation. After the model simulation reached the equilibrium state, the model was run from year 1000 to year 1900 by repeating a 30-year cycle of the 1901–1930 monthly climate data and was then run from year 1901 to year 2011 using the historical climate data. During the calibration process used by Yi *et al.* (2010) and Clein *et al.* (2002), the target ecosystem state variables and efflux were compared at the end of the equilibrium run in year 1000 to verify if the simulated variables and efflux matched the target values. This procedure worked well for the boreal forest ecosystems, but did not work satisfactorily for peatland DOS-TEM as the simulation from year 1000 to 2011 caused significant deviation from the target values. Therefore, some modification was made to the original calibration procedure used by Yi *et al.* (2010) and Clein *et al.* (2002). Instead of comparing the simulated variables with the target values at the end of the equilibrium run in year 1000, we compared the simulated means for the period 2005–2011 to the target variables.

Table 1 The target and simulated important ecosystem state variables. The variables related to the *N* cycle were estimated based on the studies of other similar ecosystems (e.g. rich fen peatlands in western Canada), while other variables were obtained from the control treatment of our rich fen peatland of APEX.

Variables	Target value	Simulated value**
Vegetation N (g m^{-2})	7.0*,†	6.8
N uptake (g m^{-2} yr^{-1})	1.0*,†,‡	1.3
Total soil N (g m^{-2})	2335*	2388
Soil available N (g m^{-2})	14.5*	14.7
Vegetation C (g m^{-2})	378§	424
Total fibric C (g m^{-2})	293	302
Total amorphous C (g m^{-2})	64055	55648
Total mineral soil C (g m^{-2})	5721	5475
Organic horizon thickness (m)	0.95	1.06
NPP (g C m^{-2} yr^{-1})	350§	285
GPP (g C m^{-2} yr^{-1})	580§	523
CH_4 efflux (mg C m^{-2} yr^{-1})	5328¶	6636
Diff. ratio (%)††	2.0‖	1.5

*Bayley *et al.* (2005)
†Vogel *et al.* (2005)
‡Ruess *et al.* (1996)
§Churchill (2011)
¶Turetsky *et al.* (2008)
‖Shea (2010).
**'Simulated value' indicates the mean simulated values from 2005 to 2011 using the daily climate data (i.e. daily precipitation) and measured soil temperature at 0, 2, 10, 25, and 50 cm. Monthly climate data were used before year 2005 during equilibrium, spin-up, and transient runs.
††'Diff. ratio' represents the contribution of diffusion transport to the total CH_4 efflux.

In addition to the target variables used by the previous versions of DOS-TEM, three additional target variables and one additional constraint condition were included in peatland DOS-TEM to better constrain the simulation of CH_4 emissions. The first additional target variable is the annual total CH_4 efflux that was estimated as the annual mean CH_4 efflux from 2005 to 2011. The second additional target variable is the contribution of soil diffusion to the total CH_4 efflux that was obtained based on the field static chamber CH_4 flux study in the control treatment of APEX (2010). The third additional target variable is the thickness of SOC horizons that was used to constrain the simulated organic soil horizons (fibric and amorphous). We also assumed that the ratios among the anaerobic decomposition rate limiting parameters (i.e. $R_{0,f}$, $R_{0,a}$, and $R_{0,m}$ in the Eqn (2) of supporting materials) were the same as those among the aerobic decomposition rate-limiting parameters; this also constrains the simulations of CH_4 emissions (the additional constraint condition).

Peatland DOS-TEM has a daily time step, and we developed the daily data for driving the model by interpolating daily values from the monthly datasets. In this study, the monthly solar radiation from 1901 to 2006 was obtained from the Climate Research Unit (CRU) of the University of East Anglia, UK, as described in detail by Hayes *et al.* (2011) and McGuire *et al.* (2010). Monthly solar radiation data from 2007 to 2011 were not available and were set to the 5-year (2002–2006) monthly mean solar radiation.

The vapor pressure from 1901 to 1989 was also obtained from CRU, but from 1990 to 2008 was calculated based on the monthly relative humidity and saturation vapor pressure. The monthly relative humidity was derived from the hourly measured relative humidity at the Bonanza Creek Experimental Forest Long Term Ecological Research site (BNZ-LTER; Hollingsworth, 2007) and the saturation vapor pressure was derived from monthly air temperature using the equation developed by Bolton (1980). The relative humidity from 2009 to 2011 was not available and the 5-year (2004–2008) mean relative humidity and air temperature were used to calculate the vapor pressure from 2009 to 2011.

The monthly precipitation and air temperature from 1901 to 1989 were obtained from CRU as discussed earlier, but those from 1990 to 2004 were derived from the hourly observations measured at BNZ-LTER (Hollingsworth, 2005). In the DOS-TEM model, the precipitation is assumed to occur twice a month, once in the beginning of month and the other time in the middle of month (Zhuang *et al.*, 2003), and daily air temperature is linearly interpolated using the monthly air temperature. To more accurately represent these two important factors in the model, for the summer (June, July, and August) of 2005–2011 when CH_4 efflux and water table were measured, the model used the daily measured precipitation (instead of interpolating from monthly precipitation) to simulate water table and soil moisture (Yi *et al.*, 2009b, 2010; Yuan *et al.*, 2012). For all other months, the model used the monthly precipitation that was obtained from either BNZ-LTER or the nearby Fairbanks weather station of the Alaska Climate Research Center (ACRC; http://climate.gi.alaska.edu). The daily soil temperature from May 2005 to September 2011 was derived using the hourly measured soil temperature at 0, 2, 10, 25, and 50 cm depths (instead of simulating soil temperature). The soil temperature above 50 cm was linearly interpolated, while the soil temperature below 50 cm was assumed to be equal to the measured soil temperature at 50 cm. This assumption is reasonable since the soil temperature below 50 cm is relatively stable during the summer (Yi *et al.*, 2009b). The soil temperature for other months of 2005–2011 was simulated using monthly air temperature and the methods described in Yi *et al.* (2009b, 2010).

The fire history for the rich-fen peatland of APEX is not known. We assumed that no fire has occurred at this site from year 1000 to 2011 and that the possibility of wildfire occurring during 2012–2099 is low, which is a reasonable assumption given the shallow water table and relatively low fuel loads (Kuhry, 1994) and the fact that there are no visible charcoal layers in soil profiles analyzed for this site (data not shown). However, our model does have the ability to simulate fire impacts in other peatland systems where fire may play a more important role in carbon dynamics.

Model validation

After the model was calibrated based on information from the control treatment of the rich fen, the measured CH_4 and CO_2 emissions from the raised and lowered water table treatments were used to validate model performance. All of the input climate datasets (i.e. air temperature, precipitation, vapor pressure, and solar radiation) from 1901–2011 for the raised and lowered water table treatments are the same as those used for the control treatment of APEX. In addition, since the summer water table in the raised and lowered treatments was manipulated from 2005 to 2011, it was not possible to use the model to simulate the water table with the precipitation data. Therefore, we used the measured summer water table position during the summer months of 2005–2011 (M. Turetsky, unpublished data; Turetsky *et al.*, 2008) to drive our simulations for these treatments. For all other months, monthly precipitation was used to simulate the soil moisture content and water table. The measured soil temperature from May 2005 to September 2011 at 0, 2, 10, 25, and 50 cm were used to drive the model for the validation simulations. For all other months, the monthly air temperature as described above for the control treatment simulation was used to simulate soil temperature in the raised and lowered water table treatments.

Model application

One of the primary purposes of peatland DOS-TEM is to use it as a tool to assess the response of peatland dynamics in interior Alaska to projected climate change. Projections of future climate (e.g. air temperature and precipitation) are most commonly available at a monthly resolution. The calibration and validation evaluations of peatland DOS-TEM were driven by daily climate inputs. Therefore, it is necessary to examine the discrepancies between C fluxes (CH_4 and ER) and water table simulated with daily climate data vs. those simulated with monthly climate data to identify whether it is suitable to predict future water table and carbon emissions with monthly climate data. To answer this fundamental question and to examine the uncertainties associated with the use of monthly climate data, we also conducted simulations from 2005 to 2011 driven by the monthly climate data. For the rich fen control treatment, the monthly precipitation derived from the daily measured precipitation was used to simulate the soil moisture for the summer of 2005–2011, and monthly air temperature was used to simulate soil temperature. For the raised and lowered treatment, monthly precipitation data were used to simulate soil moisture content and water table depth.

After it was confirmed that it is acceptable to use monthly climate data to drive peatland DOS-TEM simulations, we used the model to project and evaluate the potential SOC dynamics of the fen control treatment in response to future climate change under various CO_2 emission scenarios. Walsh *et al.* (2008) evaluated the performance of 15 global climate models (GCMs) that were used in the Fourth Assessment Report (AR4) of the intergovernmental panel on climate change (IPCC, 2007). The results of Walsh *et al.* (2008) indicated that the output of five of the fifteen GCMs best matched with the historical 1958–2000 climate datasets for Alaska. Two out of the five best GCMs were selected for this study: the model developed by Max Planck Institute for Meteorology (MPI ECHAM5, hereafter ECHAM, Hamburg, Germany) and the model developed by Geophysical Fluid Dynamics Laboratory (GFDL CM21, hereafter GFDL, Princeton, NJ, USA). In addition to the good performance over Alaska, these two models were selected because they also provide distinctly different patterns of warming and summer precipitation, which allows us to discern the roles of warming and changes in precipitation on peatland SOC dynamics. Three different CO_2 emission scenarios were considered in this study: the A2 scenario (high emissions), the B1 scenario (low emissions), and the A1B scenario (midrange emissions).

The projected changes in monthly air temperature, precipitation, and radiation for the period 2012–2099 were obtained from the IPCC's Data Distribution Centre (http://www.ipcc-data.org). The monthly mean climate from 2000 to 2011 was used as the base climate, to which the projected monthly changes were added to generate the future climate data (i.e. air temperature, precipitation, and radiation). The projected change in monthly vapor pressure (or relative humidity) from 2012 to 2099 was not available. It was assumed in this study that the relative humidity was constant from 2012 to 2099 and was equal to the mean 2000–2011 relative humidity. Vapor pressure from 2012 to 2099 was calculated based on the relative humidity and saturation vapor pressure (calculated using air temperature). The yearly atmospheric CO_2 concentrations for the period 2012–2099 were set to be the averaged values of output from the Integrated Science Assessment Model (ISAM) (Kheshgi & Jain, 2003) and the Bern Carbon Cycle-climate Model (BERN) (Joos *et al.*, 2001) for each emission scenario (i.e. A1B, A2, or B1).

The future simulations were conducted in a factorial combination of warming and precipitation changes: (1) no warming and no precipitation change (Sim00), (2) no warming and precipitation change (Sim0P), (3) warming and no precipitation change (SimT0), and (4) with both warming and precipitation change (SimTP), resulting in 24 simulations in total. We compared a historical simulation for the rich fen to Sim00 to infer the effects of increasing atmospheric CO_2 on soil organic carbon. The factorial simulations were compared to understand the impacts of warming, precipitation change, and their interactions on the total SOC pool of the control site of the rich fen, as well as the C inputs and C losses from the pool.

Statistical analysis

Statistical analysis was conducted using the data analysis tools in the Microsoft Excel (version 2010 Microsoft Corporation, Redmond, WA, USA). Correlation/regression analyses were used when the field-based estimates and model simulations were compared at the same temporal resolution. A student's *t*-test (hereafter *t*-test) for the slope in regression model was conducted to evaluate if the slope is significantly different from 1. In cases where the temporal resolution of the model (e.g. daily) was different from observations that contributed to field-based estimates (e.g. minutes for ecosystem respiration and on the order of a half hour for methane emissions), we used a two-sample *t*-test to evaluate differences between model simulations and field-based estimates. The *t*-test with two samples we used in this study assumed equal variances and we used an $\alpha = 0.05$ significance level to determine if the means of two datasets (e.g. simulation-based estimates vs. field-based estimates) were significantly different. An individual datum in the sample for the field-based flux estimates was generally the mean of three chamber measurements of flux for a particular day of sampling. An individual datum in the sample of model-based flux estimates was the flux estimate for the same day as the field-based flux estimate.

Results

Model calibration and validation

Water table is an important factor controlling peatland SOC dynamics. Although we did not use simulated water table dynamics in the calibration of peatland DOS-TEM, the model is capable of successfully reproducing the measured variability in water table from 2005 to 2011 at the rich fen control treatment (Fig. 2b; regression analysis: correlation coefficient = 0.81; slope = 0.98; *t*-test for 1 : 1 slope: $P = 0.47$). Outputs after model calibration indicate that peatland DOS-TEM successfully simulated the measured pools and fluxes of the rich fen control treatment (Table 1). The model also reproduced the measured CH_4 emissions at the rich fen control treatment from 2005 to 2011 except for the driest year in 2006 (Fig. 2a; *t*-test with year 2006, df = 94, $P = 0.02$; *t*-test without year 2006, df = 78, $P = 0.08$); in 2006 the water table dropped to the lowest recorded level of 67 cm below the surface across all the years.

Our model validation indicates that peatland DOS-TEM is able to simulate the patterns of CH_4 emissions at the lowered (Fig. 2c; *t*-test, df = 88, $P = 0.84$) and raised water table treatments except for the driest year in 2006 (Fig. 2e; *t*-test with year 2006, df = 82, $P = 0.03$; *t*-test without year 2006, df = 66, $P = 0.26$). There are three extremely large CH_4 efflux measurements that are not captured by the model and are not shown in Fig. 2 to avoid data clustering. These include two measurements for the lowered water table treatment (427 and 231 mg CH_4-C m^{-2} day^{-1} on July 15, 2009 and September 14, 2009, respectively) and one measurement for the raised water table treatment (199 mg CH_4-C m^{-2} day^{-1} on June 15, 2009). To further validate the performance of the model, we also compared the simulated summer monthly ecosystem CO_2 respiration (ER) to the ER measured with static chamber techniques. ER is calculated in the model as the sum of autotrophic and heterotrophic respiration, CO_2 produced under anaerobic conditions, and CO_2 produced during the microbial oxidation of CH_4 in the oxic zone. Autotrophic respiration is the sum of plant growth and maintenance respiration. The simulated summer monthly ER is not significantly different from the measured summer monthly ER (Fig.3; t-test, control treatment: df = 54, P = 0.11; lowered water table treatment: df = 50, P = 0.81; raised water table treatment: df = 46, P = 0.86)(Chivers *et al.*, 2009; Churchill, 2011; N. McConnell, unpublished data).

The simulated monthly mean water table of the control treatment driven by monthly precipitation is overall not significantly different from water table driven by daily precipitation (Fig. 4; regression analysis: correlation coefficient = 0.93; slope = 1.12; t-test for 1:1 slope: P = 0.28); however, the difference between water table driven by monthly and daily precipitation increases when water table is deeper than 40 cm. The simulated monthly mean soil temperature (0–50 cm in June, July, and August) driven by monthly air temperature also is not significantly different from monthly mean measured soil temperature (Fig. 4; regression analysis: correlation coefficient = 0.96; slope = 0.85; t-test for 1 : 1 slope: P = 0.34). The simulated monthly CH_4 emissions driven by monthly climate data for the control, raised, and lowered treatments of the APEX water table manipulation experiment are not significantly different from the simulations driven by daily climate data (Fig. 5. Regression analysis, control

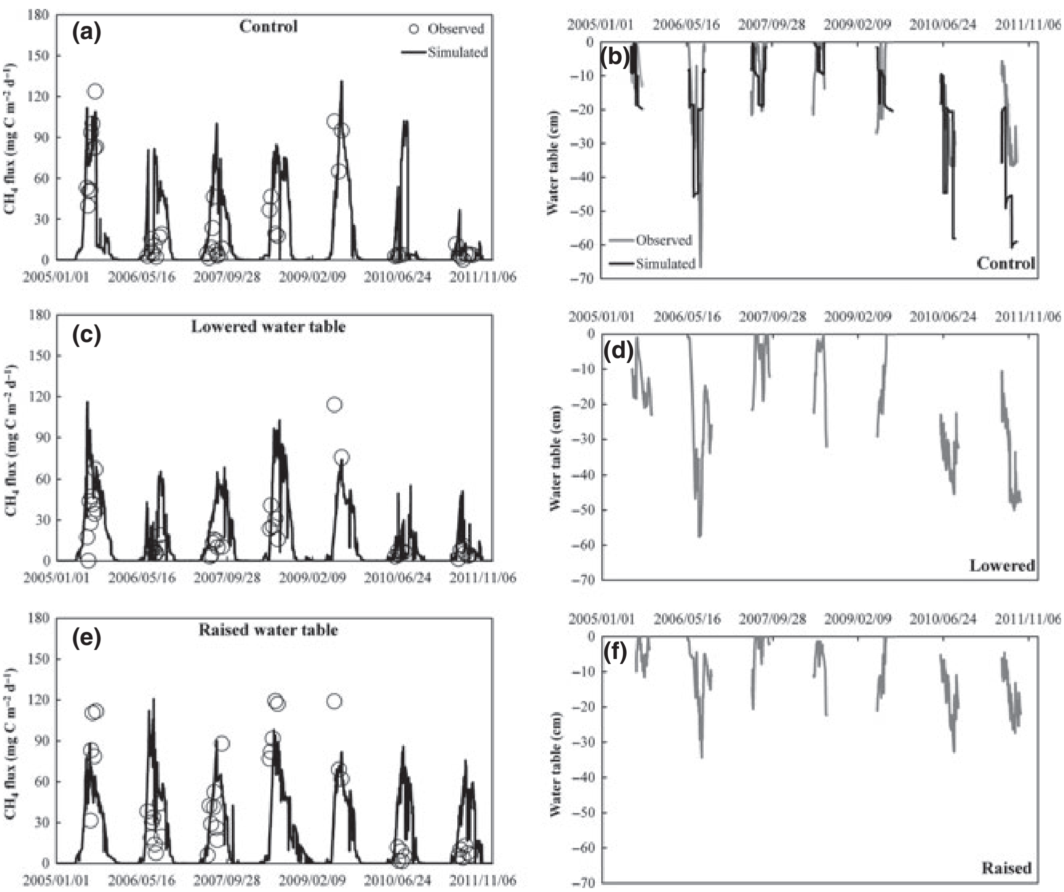

Fig. 2 The measured and simulated CH_4 efflux for the control (a), lowered (c), and raised (e) water treatments of America Peatland Experiment (APEX) from 2005 to 2011 using the daily driving climate data. For all of the three treatments, soil temperature was not simulated, but linearly interpolated from daily measured soil temperature at 0, 2, 10, 25, and 50 cm. The soil temperature below 50 cm was set to be equal to the soil temperature measured at 50 cm. For the control treatment, both CH_4 efflux and water table (b) were simulated using the daily precipitation. For the lowered and raised water table treatments, CH_4 efflux was simulated using the daily precipitation along with the measured water table (d and f). Three extremely large CH_4 efflux measurements including two measurements for the lowered water table treatment (427 and 231 mg CH_4-C m^{-2} day^{-1} on July 15, 2009 and September 14, 2009, respectively) and one measurement for the raised water table treatment (199 mg CH_4-C m^{-2} day^{-1} on June 15, 2009) are not shown here to avoid data clustering.

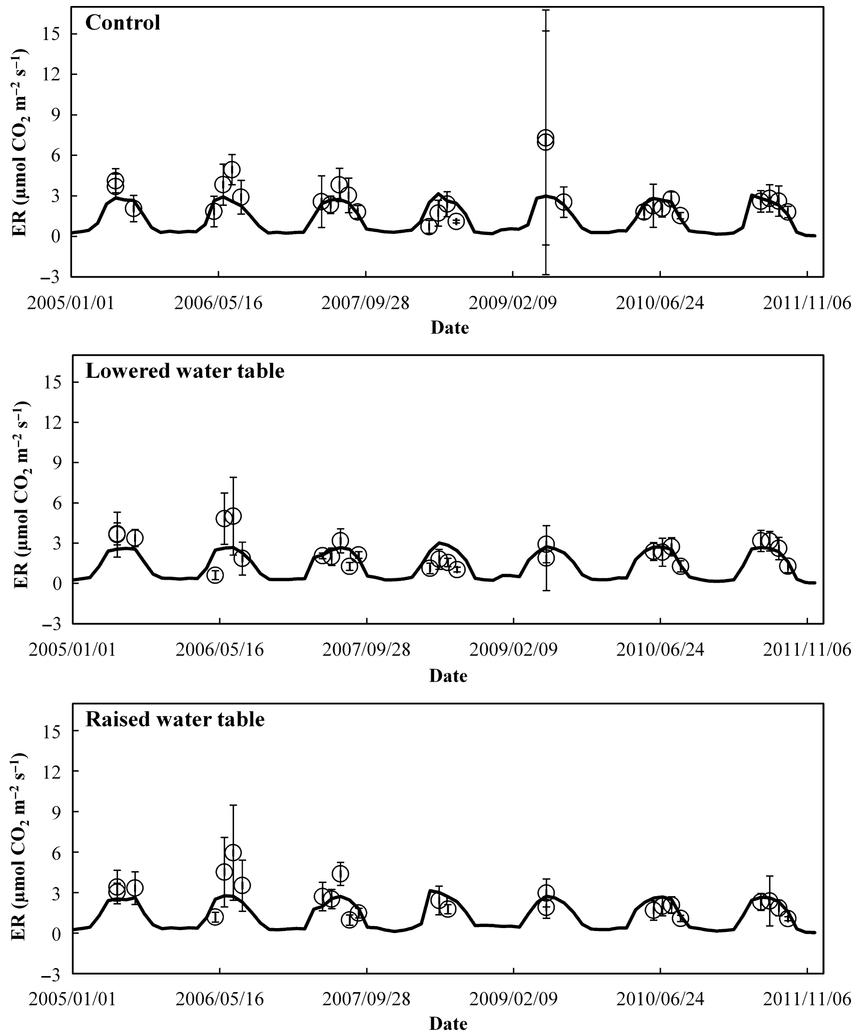

Fig. 3 The measured and simulated ecosystem respiration (ER) for the control, lowered, and raised water treatments of Alaska Peatland Experiment (APEX) from 2005 to 2011 using the daily driving climate data. Error bars indicate standard deviation.

treatment: correlation coefficient = 0.94; slope = 1.03; *t*-test for 1 : 1 slope: P = 0.16. Lowered water table treatment: correlation coefficient = 0.98; slope = 1.15; *t*-test for 1 : 1 slope: P = 0.08. Raised water table treatment: correlation coefficient = 0.97; slope = 1.14; *t*-test for 1 : 1 slope: P = 0.08). The simulated monthly ER driven by monthly climate data are not significantly different from ER simulated with daily climate data (Fig. 5. Regression analysis, control treatment: correlation coefficient= 0.99; slope = 0.95; *t*-test for 1 : 1 slope: P = 0.12. Lowered water table treatment: correlation coefficient = 0.99; slope = 0.91; *t*-test for 1 : 1 slope: P = 0.08. Raised water table treatment: correlation coefficient = 0.99; slope = 0.89; *t*-test for 1 : 1 slope: P = 0.07). The partitioning of ER is similar between the simulations driven with monthly and daily climate data. There is no significant difference between the simulated contribution of heterotrophic respiration with daily climate data and that simulated with monthly climate data (Fig. 6. Regression analysis, control treatment: correlation coefficient = 0.96; slope = 1.08; *t*-test for 1 : 1 slope: P = 0.08. Lowered water table treatment: correlation coefficient = 0.99; slope = 0.98; *t*-test for 1 : 1 slope: P = 0.11. Raised water table treatment: correlation coefficient = 0.99; slope = 0.98; *t*-test for 1 : 1 slope: P = 0.22). Taken together, the various aspects of this temporal scaling analysis indicate that it is acceptable to use monthly climate data to drive peatland DOS-TEM simulations.

Model application

We applied peatland DOS-TEM to simulate the future SOC dynamics of the rich fen control treatment driven by temperature and precipitation projected by the ECHAM and GFDL models under three CO_2 emission

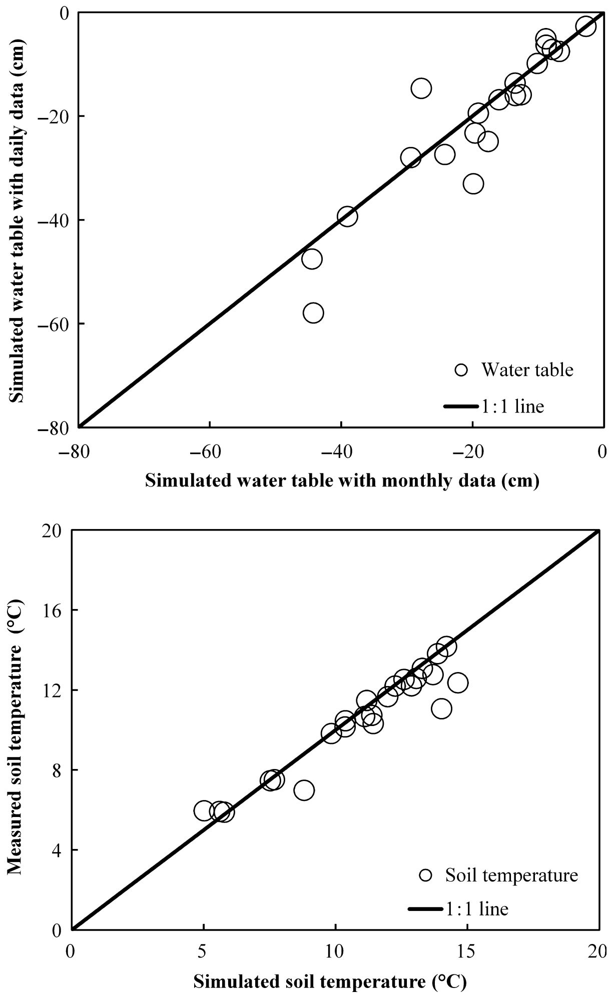

Fig. 4 The comparison of water table simulated using daily precipitation and measured soil temperature vs. water table simulated using monthly precipitation and air temperature and using simulated soil temperature for the control treatment (top panel). The comparison between mean measured 0–50 cm soil temperature and mean 0–50 cm soil temperature simulated with monthly climate data (i.e. precipitation and air temperature) for the control treatment (bottom panel).

scenarios (A1B, A2, and B1). The projected air temperature, precipitation, and atmospheric CO_2 concentration from 2012 to 2099 that were used to drive the simulations are shown in Fig. 7. In general, ECHAM projects higher summer mean temperature and lower summer total precipitation than GFDL.

The historical simulation from 1901 to 2011 indicates that the control treatment was a net sink for carbon of 2.4 g SOC m^{-2} yr^{-1} with annual inputs of 204 g C m^{-2} yr^{-1} and annual losses of 196 g CO_2-C m^{-2} yr^{-1} and 6.0 g CH_4-C m^{-2} yr^{-1} (Fig. 8). In comparison to the historical simulation, the simulations driven by changes in climate and atmospheric CO_2 indicate that the cumulative SOC sequestration will start to decrease as early as year 2061 for the simulations driven by GFDL A1B (Fig. 9). Therefore, the analysis of the future simulation is divided into two time periods, 2012–2061 and 2062–2099. The C inputs, soil SOC stock changes, CO_2 and CH_4 efflux for these two time periods are shown in Fig. 8. From 2012 to 2061, the rate of SOC sequestration in the rich fen peatland increases for all of the six Sim TP simulations in comparison to simulated historical SOC sequestration (Fig. 8, also see Fig. 9). However, from 2062 to 2099, the rich fen peatland is projected to lose SOC for ECHAM A1B and B1 and GFDL A1B and A2 climate scenarios (Figs 8 and 9). The rates of SOC sequestration for ECHAM A2 and GFDL B1 scenarios is also projected to be weakened compared to the rate of SOC sequestration from 2012 to 2061 (Figs 8 and 9), but are greater than the simulated historical rate of SOC sequestration. In general, inputs into the SOC pool and CO_2 and CH_4 emissions increase in comparison to the historical simulation. The analyses below focus on understanding the relative roles of increases in atmospheric CO_2 and changes in climate on these results.

To evaluate the role of atmospheric CO_2 and other factors (i.e. changes in radiation and vapor pressure) on future SOC dynamics of the control treatment, we compared the Sim00 simulations, which were driven by detrended temperature and precipitation, with the historical simulation. In comparison to the historical simulation, the Sim00 simulations indicate that C inputs into the soil and heterotrophic respiration increase substantially (Fig. 8). These changes in inputs and losses cause the SOC pool of the Sim00 simulations to increase between 8.0 and 12.4 g C m^{-2} yr^{-1} for 2012–2061 and between 5.6 and 22.9 g C m^{-2} yr^{-1} for 2062–2099. Thus, we interpret the substantial increases of C inputs into the SOC pool and the substantial increases in losses from the SOC pool in the SimTP simulations as primarily being driven by the response of peatland DOS-TEM to increases in atmospheric CO_2, changes in radiation, and changes in vapor pressure.

The simulation results of Sim00 (driven by detrended future temperature and detrended future precipitation) are considered as the reference to which we compare with other simulations to examine the roles of warming and changes in precipitation on SOC dynamics. The comparison of the simulation results between SimTP and Sim00 indicates that both warming and changes in precipitation cause decreases in SOC sequestration rate under all of the three emission scenarios for both ECHAM and GFDL between 2012 and 2099. The simulations also indicate that climate change leads to an increase in both CH_4 emissions and heterotrophic respi-

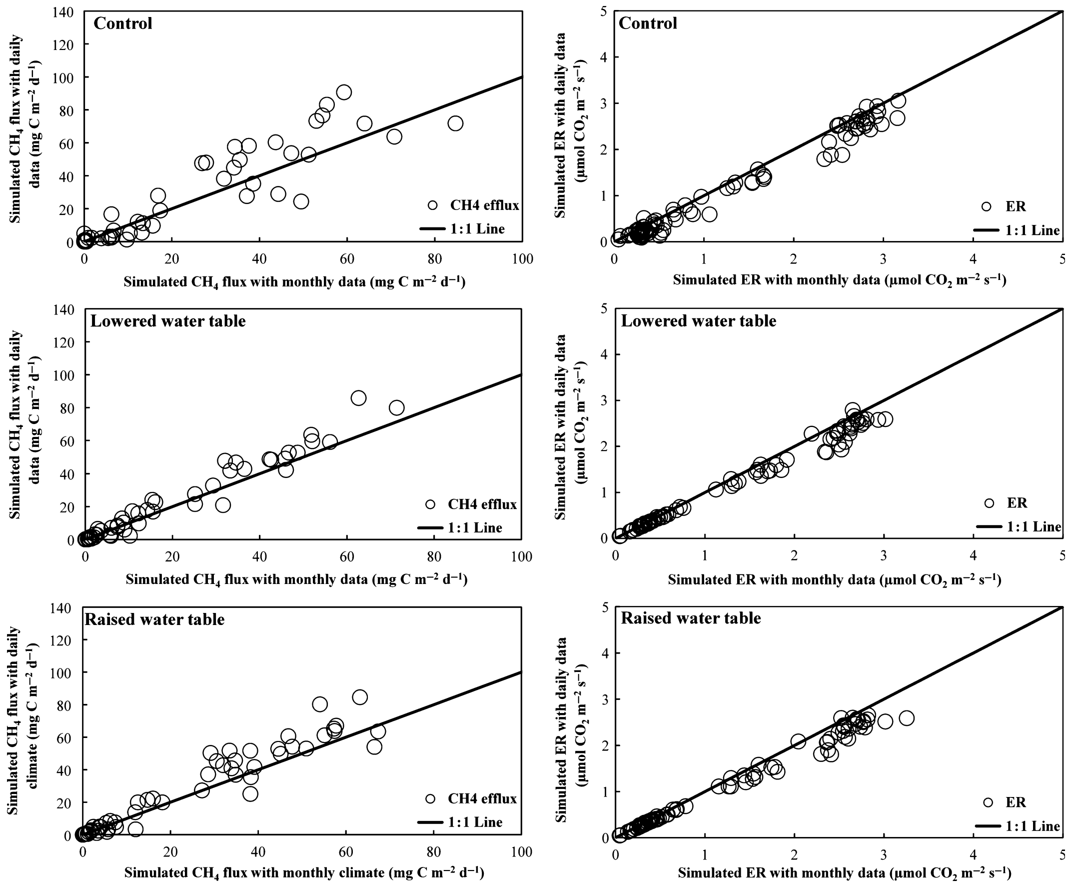

Fig. 5 The comparisons of CH_4 efflux and ecosystem respiration (ER) simulated using daily precipitation and measured soil temperature vs. CH_4 efflux and ER simulated using monthly precipitation and air temperature and using simulated soil temperature for the control, lowered, and raised water table treatments.

ration under all of the three emission scenarios for ECHAM and GFDL between 2012 and 2099.

Analysis of the SimT0 and Sim0P simulations in comparison to the Sim00 and SimTP simulations in Fig. 8 indicates that warming is responsible for most of the SOC loss that occurred between the Sim00 and SimTP. For the SimT0 simulations driven by ECHAM this was primarily due to higher heterotrophic respiration in response to warming. In contrast, the greater decrease in SOC pools for the SimT0 simulations driven by GFDL climates were caused by lower inputs into the SOC pool. However, the comparison of the SimTP with the SimT0 climates driven by the GFDL climates reveals that changes in precipitation interact with warming as carbon inputs into the SOC pool are increased above those of the Sim00 simulations. This is accompanied by an increase in heterotrophic respiration in the SimTP GFDL simulations compared with the Sim00, SimT0, and Sim0P simulations. In the simulations driven by both ECHAM and GFDL climate inputs, both warming and precipitation change decreased CH_4 emissions in comparison to Sim00.

Discussion

Model performance

The model calibration demonstrates that peatland DOS-TEM can reproduce the observed pools and fluxes of the rich fen control treatment. The comparisons between the target and simulated ecosystem variables suggest that the model accurately represents important ecosystem processes and states (e.g. NPP, N dynamics, SOC pool mass and thickness, losses of CO_2 and CH_4 to the atmosphere, etc.) in boreal rich fens. The model validation also suggests that peatland DOS-TEM is capable of simulating responses of this ecosystem to field water table manipulations.

Comparison of simulations to measurements suggests that there are some discrepancies between the simulated and measured water table and CH_4 efflux. Several main uncertainties associated with the model structure may be responsible for these discrepancies. The first uncertainty associated with our model is the model dimension. Currently, the soil thermal and mois-

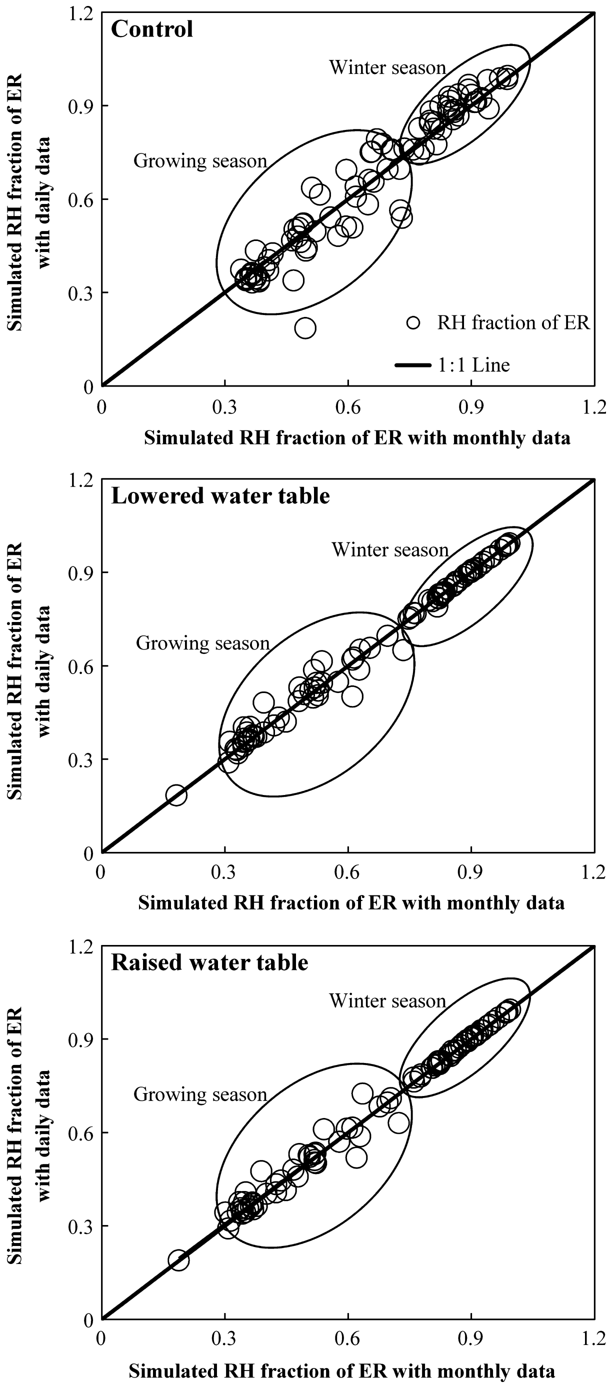

Fig. 6 The comparisons of simulated heterotrophic respiration (RH) fraction of ecosystem respiration (ER) using daily precipitation and measured soil temperature vs. RH fraction of ER simulated using monthly precipitation and air temperature and using simulated soil temperature for the control, lowered, and raised water table treatments.

ture components of DOS-TEM model are one-dimensional. However, the potential and complex water exchange between the peatland and groundwater (likely affected by the nearby Tanana River) may significantly affect the water table due to lateral and/or ground water flow (B. Cable, personal communication; Racine & Walters, 1994). Detailed surveys on the regional groundwater flow network along with a three-dimensional coupled water and heat transport model are needed to understand and simulate the peatland local water flow and nutrient transport. Second, the abundance and biomass of vascular plants remains constant in the model. However, the substantial inter-annual variation in water table in this system influences the abundance and biomass of vascular plants, which is likely to have important implications for CH_4 efflux (Finer & Laine, 1998). Third, many studies have shown that labile carbon derived from dead plant matter and root exudates can stimulate SOC decomposition via priming effects (Fontaine *et al.*, 2007; Zhu & Cheng, 2010). Such soil-root interactions and the transport of labile carbon through the soil profile may have great impacts on methanogenesis and decomposition; these effects were not considered in our model, but deserve more attention. One of the possible solutions to discern the priming effects is to include the microbial and/or enzyme activities (e.g. microbial death and growth) in our current carbon models. Fourth, the root distribution is pre-defined in DOS-TEM and maintained constant throughout the simulation (Yi *et al.*, 2010; Yuan *et al.*, 2012). A dynamic vegetation model along with an adapting root dynamics component may improve the representation of the root and vegetation dynamics and thus the plant-mediated CH_4 emissions and nutrient/water uptake in response to climate change (Schymanski *et al.*, 2008). Finally, besides soil temperature and moisture, the production of CH_4 in the saturated zone is also controlled by soil geochemical conditions (e.g. redox potential and electron acceptors). Further laboratory studies considering alternative electron acceptors (including dissolved humic substances) are necessary to model anaerobic SOC decomposition.

The CH_4 emission estimates used to calibrate the model were based on flux measurements collected every 1–2 weeks during the summers of 2005–2011 (Turetsky *et al.*, 2008). Statistical uncertainties may exist when representing large temporal-resolution (i.e. annual) efflux with discontinuously measured sub-daily emissions. However, although such uncertainty may affect the magnitude of simulated CH_4 emissions, they are unlikely to affect the trends and patterns of seasonal and annual CH_4 emissions.

There were two very large CH_4 emission events in the lowered water table treatment and one large CH_4 emission event in the raised water table treatment. All of the three emission events occurred in 2009 (flooding year) and are not captured by our model. This might

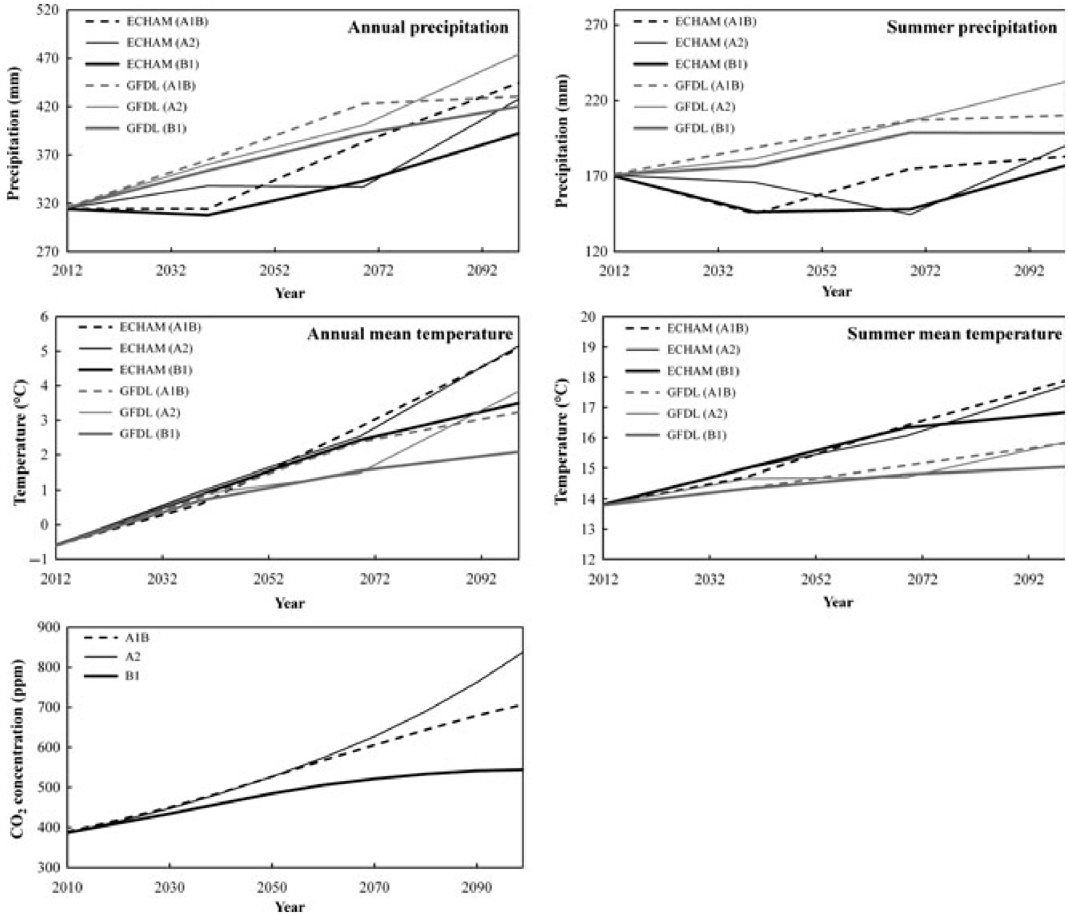

Fig. 7 The projected annual mean air temperature and precipitation, mean summer air temperature, and total summer precipitation from 2012 to 2099 by ECHAM and GFDL under three CO_2 emission scenarios: the midrange emission (A1B), the high emission (A2), and the low emission (B1). The mean monthly air temperature and precipitation from 2000 to 2011 were used as the base air temperature and precipitation. The projected changes in air temperature and precipitation by ECHAM and GFDL were added to the base air temperature and precipitation to generate the future air temperature and precipitation. The CO_2 concentration is the averaged value of output of ISAM and BERN model.

be partially due to the relatively dense soils and low methane storage capacity in the rich fen peatlands of APEX (M. Turetsky, unpublished data), suggesting that the ebullition in our model may not be adequately represented. In addition to concentration and temperature, the heterogeneous nature of CH_4 ebullition is also controlled by soil gas composition, soil physical properties (e.g. pore connectivity), barometric pressure, plant functional types, and peat properties (Baird *et al*., 2004; Goodrich *et al*., 2011; Comas & Wright, 2012). Therefore, an improved ebullition model considering these factors along with additional field experiments may be helpful to better understand and model gas ebullition events in peatlands.

Although the statistical differences between simulated CH_4 flux with daily and monthly climate data are not significant, the differences likely become relatively large when the CH_4 fluxes are greater than 20 mg C m^{-2} d^{-1}. This might be caused by the fact that precipitation was assumed to occur only twice a month in our model (once at the beginning of month and the other time in the middle of month) when monthly climate data were used to drive the model (Yi *et al*., 2009b). The greater than normal amount of precipitation during each of the two precipitation events likely causes greater runoff and/or surface evapotranspiration, resulting in a deeper water table and thus lower CH_4 flux than simulated with daily climate data.

Responses to changes in climate and atmospheric CO_2

The results from the application of peatland DOS-TEM across the emissions scenarios suggest an initial increase in C sequestration rate between 2012 and 2061;

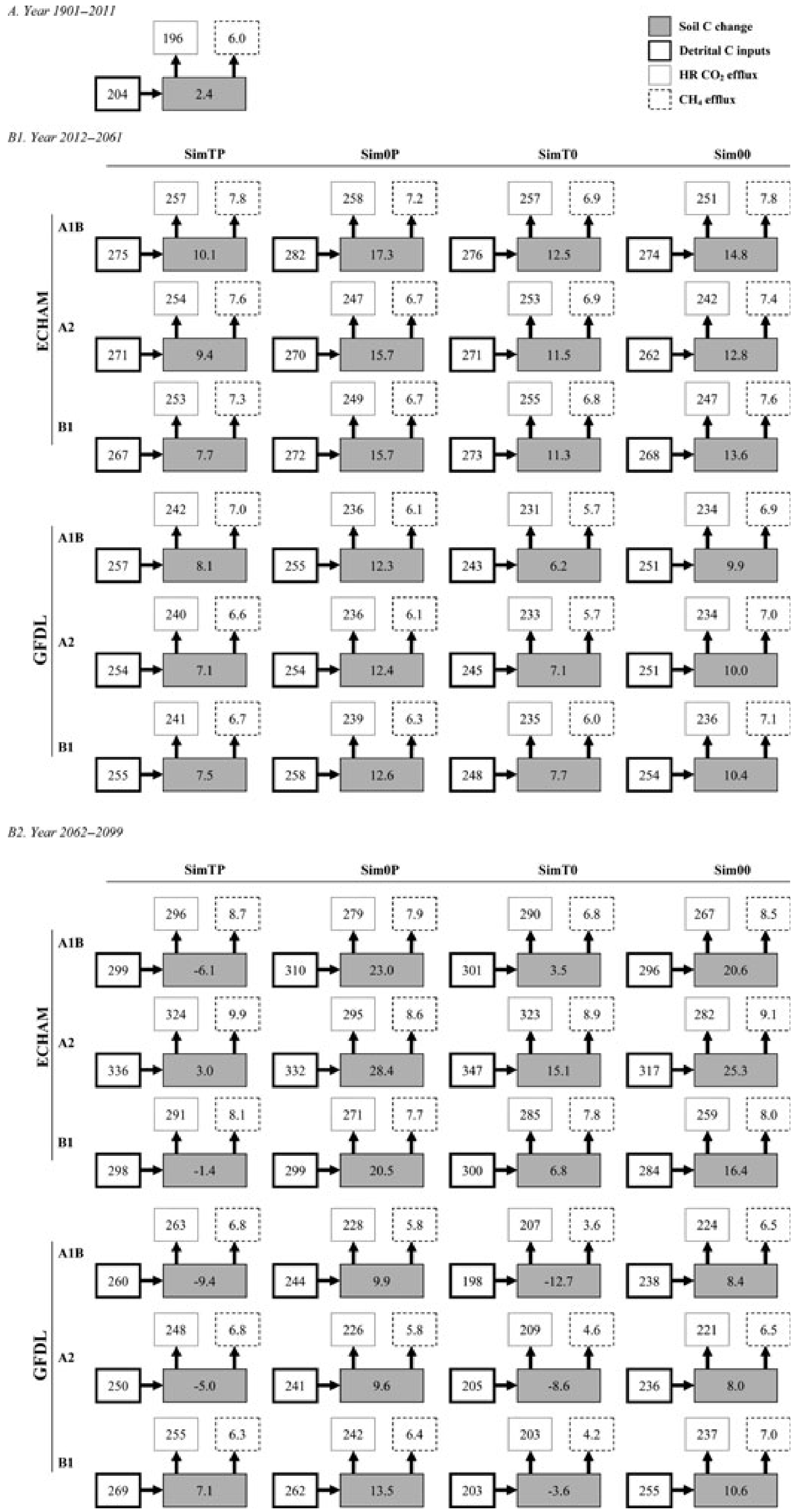

Fig. 8 The simulated soil organic carbon stock change, soil organic carbon input, and CO_2 and CH_4 fluxes by peatland DOS-TEM for ECHAM and GFDL under three warming scenarios (i.e. A1B, A2, and B1) from Year 2012–2061 and Year 2062–2099. The unit is g C m^{-2} yr^{-1}.

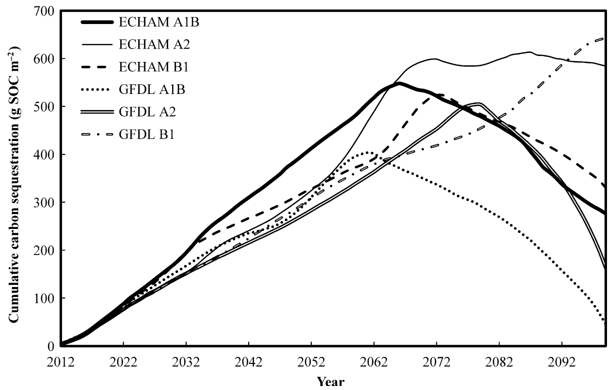

Fig. 9 The simulated cumulative carbon sequestration by peatland DOS-TEM for ECHAM and GFDL under three warming scenarios (A1B, A2, and B1) from 2012 to 2099.

however the rich fen peatlands will likely turn into SOC sources between 2062 and 2099 under the projected climate change because warming increases heterotrophic respiration more than rising atmospheric CO_2 increases carbon inputs into the soil. The ratio of CO_2 to CH_4 emissions increases because the emissions of CO_2 from the rich fen were more sensitive to plant-mediated responses to CO_2 concentration and climate. Our comparison of the Sim00 simulations (in which temperature and precipitation were detrended) to the historical simulation and to the SimTP simulation (in which temperature and precipitation were not detrended) indicates that most of the response of CO_2 and CH_4 emissions in SimTP is associated primarily with increasing atmospheric concentration of CO_2 and changes in radiation. Temperature and precipitation also have influences that further affect the response of CO_2 and CH_4 emissions in SimTP. Our inference is that most of the response in the Sim00 simulations is associated with increasing atmospheric CO_2, but that the response has been modified by changes in radiation. Increasing atmospheric CO_2 concentration increases CO_2 and CH_4 emissions from SOC in peatland DOS-TEM simulations by increasing the inputs of C into the SOC pool. The responses are consistent with the study of Freeman *et al.* (2004) who argue that CO_2 fertilization in peatlands results in increased inputs into the soil. Also, it has been demonstrated that CH_4 emissions in wetlands can be enhanced by elevated CO_2 (Dacey *et al.*, 1994; Hutchin *et al.*, 1995; Megonigal & Schlesinger, 1997). Several studies have documented that vegetation growth is substantially limited by the availability of nutrients in peatlands subject to elevated CO_2 concentrations (Berendse *et al.*, 2001; van der Heijden *et al.*, 2000; Woodin *et al.*, 1992). The effect of CO_2 fertilization on NPP in our simulations is substantially 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 process-based models that do not consider the effects of N constraints (Kicklighter *et al.*, 1999; McGuire *et al.*, 2001). However, it is expected that the response of NPP to CO_2 fertilization should be less constrained in a rich fen system than that in nutrient poor fens and bogs. Thus, the response of CO_2 and CH_4 emissions to rising atmospheric CO_2 in peatland DOS-TEM simulations appears to be generally consistent with studies that have manipulated CO_2 in wetland ecosystems, but may be overestimated by not considering the loss of DOC as discussed below.

After accounting for the effects of increasing atmospheric CO_2, our analysis suggests that warming (as indicated by SimT0) will play a relatively more important role in controlling peatland SOC dynamics in comparison to changes in precipitation (as indicated by Sim0P). This finding is similar to the analyses of Lafleur *et al.* (2003) and Fan *et al.* (2008), which suggest that SOC stocks in an ombrotrophic bog and a poorly drained black spruce site were more sensitive to temperature than moisture. Although changes in precipitation alone had relatively little impact on peatland SOC dynamics compared to warming, the combined effects of warming and change in precipitation (as indicated by SimTP) did influence carbon inputs and heterotrophic respiration for the simulations driven by GFDL climates. There are several ways that changes in precipitation may interact with changes in temperature to influence SOC dynamics. First, precipitation change affects the soil moisture content as well as soil thermal properties (e.g. soil apparent heat capacity), which influences soil temperature and warming propagation in soils (O'Donnell *et al.*, 2009; Fan *et al.*, 2011). Second, warming also affects soil moisture by changing ecosystem evapotranspiration in peatland DOS-TEM (Yi *et al.*, 2009b). Finally, interactions between changes in soil moisture and temperature not only affect SOC losses but also might substantially change the input of carbon into the SOC pool by changing the length of the plant growing season and soil N cycling (e.g. N mineralization) to affect NPP.

The relative effects of climate change on CO_2 and CH_4 emissions

The simulated CO_2: CH_4 ratio from year 1901 to 2011 falls within the molar-ratio range for subarctic fen peatlands reported by Moore & Knowles (1989). The responses of peatland DOS-TEM suggest that the molar ratio between CO_2 and CH_4 emissions increases under all of the three emission scenarios. The increase in the CO_2: CH_4 ratio is primarily caused by increases in

CO_2 emissions and the relative insensitivity of CH_4 emissions.

A simplified approach was used to simulate anaerobic CO_2 production as a function of aerobic CO_2 production based on the published results of laboratory incubation experiments. CO_2 can be produced through anaerobic decomposition by the breakdown of complex organic molecules, which can undergo fermentation. Fermentation products, in turn, serve as electron donors in the sequential reduction of inorganic compounds in the production of CO_2 (e.g. Keller & Bridgham, 2007). These processes are controlled by soil microbial dynamics and electron donor/acceptor pools and reactions (e.g. denitrification and sulfate reduction) that strongly depend on the soil geochemical conditions and are variable from site to site, and which may be altered in the context of climate change. Many studies (e.g. Blodau & Moore, 2003; Heitmann *et al.*, 2007; Kane *et al.*, 2012) suggest that the fluctuations of water table in peatlands could suppress or replenish the supply of electron acceptors, which may, in turn, decrease or stimulate anaerobic CO_2 production. However, the pathways and the underlying mechanisms of anaerobic CO_2 production are still poorly understood. Keller & Bridgham (2007) indicated that 29–85% of anaerobic CO_2 production cannot be explained with denitrification, iron/sulfate reduction, and methanogenesis suggesting that additional underlying mechanisms (e.g. humic acid reduction) may be very important to anaerobic CO_2 production. These issues, in their current state, cannot be evaluated through mechanistically based modeling approaches, but deserve more attention in the future development of peatland DOS-TEM to reduce uncertainties in simulating future CO_2 and CH_4 responses in boreal peatlands.

The importance of DOC losses

In addition to CO_2 and CH_4 losses, another potential SOC loss pathway in peatlands/wetlands is via the formation and export of DOC, which is not currently represented in peatland DOS-TEM. DOC concentrations in peat porewater depend on the accumulation of water soluble products from decomposition and plant tissue decomposition, leachates, and exudates (Qualls *et al.*, 1991; Munch *et al.*, 2002). DOC may be exported from soils to aqueous ecosystems (e.g. rivers, lakes, or oceans) before being completely decomposed by soil microorganisms, provided sufficient hydrological connectivity. Blodau *et al.* (2004) estimated that the export of DOC from peatlands can account for approximately 59–72% of total SOC losses (i.e. sum of DOC export and CO_2 and CH_4 emissions) in two Canadian acidic and oligotrophic peatlands with raised water tables (2–6 cm below moss cover). The responses of DOC export to climate change (i.e. increasing or decreasing export of DOC from soils) are still debated (Tranvik & Jansson, 2002; Freeman *et al.*, 2004). Although some empirical approaches (e.g. Frolking *et al.*, 2002) have been used to simulate DOC export in boreal peatlands, few process-based DOC models (e.g. Yurova *et al.*, 2008; Fan *et al.*, 2010) have been developed and tested in the boreal region. Most of current process-based DOC models are focused on examining the individual soil processes that are important to DOC transport and have not been integrated with soil ecosystem models to examine interactions between DOC dynamics and other ecosystem states and processes. Information on the export of DOC and the corresponding surface and subsurface flow network within and nearby the APEX site are still very limited (Kane *et al.*, 2010; Wyatt *et al.*, 2012). Further field and modeling studies are needed to address DOC dynamics in peatlands/wetlands and the potential export of DOC in the context of increasing atmospheric CO_2 concentration and climate change.

Broader implications of our findings

Although there are many uncertainties in our modeling analysis, our findings do have broader implications if they represent more general responses of peatland carbon storage to climate change in northern high latitude regions. Rich fens have been studied less than *Sphagnum*-dominated bogs and poor fens, but represent one of the most common peatland types in boreal North America. Throughout the Holocene, it is estimated that carbon sequestration of northern peatlands has had a net cooling effect on the climate system (Frolking & Roulet, 2007; Frolking *et al.*, 2011). Our results suggest that the pattern of SOC sequestration in the APEX rich fen is likely to transition to becoming a carbon source in the latter half of this century. The weakening of terrestrial sinks has important implications for international climate policy to manage the global carbon cycle. Efforts to assess the efficiency of terrestrial sinks have largely been conducted at the global scale (Canadell *et al.*, 2007; Le Quere *et al.*, 2009), but it is important that the assessment of the efficiency of sinks incorporate regional details and insights to better understand how and why sink strength is changing to better inform climate policy related to the management of the global carbon cycle (Canadell *et al.*, 2011). Because of the large amount of carbon stored in northern peatlands, it is important to assess whether or not the sink strength of northern peatlands will generally weaken. Our results suggest that the rich fen peatland might shift from a net sink to a net source of C at the end of 21st century because both productivity and respiration of rich fen peatland ecosystems are more sensitive to warming and changes in atmospheric CO_2 concentration than to changes in precipitation, and because the respiration response exceeds the production response as temperatures rise. A next step of our modeling efforts is to develop the capability of using the peatland DOS-TEM modeling framework we have developed to assess the responses of peatland soil organic carbon to climate change at a regional scale throughout interior Alaska.

Acknowledgements

This research was accomplished with support from the National Science Foundation for the APEX project (NSF; DEB-0425328, DEB-0724514, DEB-0830997), and support from the Bonanza Creek Long-Term Ecological Research program (funded jointly by NSF Grant DEB-0620579, and by USDA Forest Service Pacific Northwest Research Grant PNW01-JV11261952-231). We thank the numerous postdoctoral scientists, students, and technicians that have helped to collect data at the APEX sites, in particular Molly Chivers, Claire Treat, Gordon Shelter, Bill Cable, Ronnie Daanen, Collin Macheel, Amy Churchill, Nicole McConnell, Katie Shea, and Sara Klapstein. The authors also greatly appreciate the helpful comments from Steve Frolking (University of New Hampshire, USA) and two anonymous reviewers.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1 Description of peatland DOS-TEM.