Climate change reduces the capacity of northern peatlands to absorb the atmospheric carbon dioxide: the different responses of bogs and fens

Jianghua Wu (1, 2), Nigel T. Roulet (2)

(1) Sustainable Resource Management, Grenfell Campus, Memorial University of Newfoundland, Corner Brook, NL, A2H 5G4, Canada

(2) Department of Geography and Global Environmental and Climate Change Center (GEC3), McGill University, Montreal, QC, H3A 0B9, Canada

Correspondence author: Jianghua Wu, Ph.D., Assistant Professor, Sustainable Resource Management, Grenfell Campus, Memorial University of Newfoundland, 20 University Drive, Corner Brook, NL, A2H 5G4, Canada
Tel: 001-709-639-2735 Fax: 001-709-639-8125
Email: jwu@grenfell.mun.ca

Running title: Peatlands switch to C sources by 2100
Abstract

The carbon (C) storage of northern peatlands is equivalent to ~34-46% of the ~795 Tg C currently held in the atmosphere as CO$_2$. Most studies report that northern peatlands are a sink of between 20 and 60 g CO$_2$-C m$^{-2}$ yr$^{-1}$. Since peatland hydrology and biogeochemistry are very closely related to climate, there is concern whether northern peatlands will continue to function as C sinks with climate change. We used a coupled land surface scheme and peatland C model, called CLASS3W-MWM, to examine the sensitivity of peatland C to climate change. Based on the data available to constrain our model, we simulated the C dynamics of the Mer Bleue (MB) bog in eastern Canada and the Degerö Stormyr (DS) poor fen in northern Sweden for four IPCC climate change scenarios, i.e. A1B, A2, B1 and Commit, over four time periods, i.e. present day, 2030, 2060 and 2100.

When the simulated future C fluxes were compared to the baseline fluxes under the present climate conditions we found fens were much more sensitive to climate change than bogs. Gross primary production (GPP) at MB significantly increased by 4-44% up to 2100 for all scenarios except Commit. GPP at DS significantly decreased by 34-39% for A1B and A2, and slightly increased by 6-10% for B1 and Commit. Total ecosystem respiration (TER) significantly increased by 7-57% for MB and 4-34% for DS up to 2100 for all scenarios except Commit. Net ecosystem production (NEP), therefore, significantly decreased. The bog, however, was still a C sink up to 2100, though much reduced, but the fen switched to a C source for A1B and A2 scenarios. Additional experiments where we climatically transplanted the study peatlands or forced vegetation changes when the fen became too dry showed similar but less dramatic results as the standard runs. Our results indicate that northern peatlands should be included in the C-coupled climate model to fully understand the response of C cycling in terrestrial ecosystems to climate change and to reduce the uncertainties for projecting the future climate.
Key points:

- Models predict fens are more sensitive to climate change than bogs
- Future climate scenarios reduce bog C sinks and switch fens to sources
- Thus C sinks in high latitude wetlands are predicted to decrease in future

**Key words:** Northern peatlands; bogs; fens; climate change; C cycling; emission scenarios; C sinks; C sources; McGill Wetland Model; CLASS3W-MWM.
1 Introduction

Northern peatlands have stored ~450 G t carbon (C) (1 G t C=1×10^{15} g C) due to their persistently larger plant production than decomposition for thousands of years [Gorham, 1991; Turunen et al., 2002; Bridgham et al., 2006]. They store ~20% of the global soil C, which is equivalent to half of the mass of atmospheric C [IPCC, 2007]. Moreover, northern peatlands contribute about 10% to global natural methane (CH\textsubscript{4}) emissions from wetlands [Mikaloff-Fletcher et al., 2004]. Under the present climate variability, observations have shown that northern peatlands (both bogs and fens) function as small C sinks (up to 60 g C m\textsuperscript{-2} yr\textsuperscript{-1}) [Lafleur et al., 2003; Roulet et al., 2007; Nilsson et al., 2008; Sagerfors et al., 2008].

In northern peatlands, the hydrology and biogeochemistry are tightly coupled to climate [Holden, 2005; Bridgham et al., 2008; Ise et al., 2008; Frolking et al., 2009; Wu, 2009, 2012]. For example, peat temperature and soil moisture are key determinants in maintaining lower decomposition rates. Climate change is expected to be greater at high latitudes (IPCC, 2007) where most of the northern hemisphere peatlands are located (Roulet, 2000). Warmer temperatures and possibly drier conditions have been projected for these high latitudes [Meehl et al., 2007]. This change raises concerns over whether northern peatlands will remain C sinks under the changing climate.

Northern peatlands, characterized by their hydrology and vegetation composition [Bridgham et al., 2008], can be subdivided into bogs and fens [Roulet, 2000; Bridgham et al., 2006]. Bogs receive water and nutrients from precipitation, whereas fens receive additional water and possibly nutrients from surface runoff and surrounding groundwater [Rydin and Jeglum, 2006]. The differences in water supply and nutrients between bogs and fens result in differences in soil chemistry, hydrology, nutrient availability and vegetation structure [Rydin and Jeglum, 2006]. These biophysical and geochemical differences lead to the possible differences in biogeochemical processes and greenhouse gas fluxes [Bridgham et al., 2008].
Therefore, bogs and fens are expected to respond differently to climate variability and change. Field manipulative experiments show that fens are more sensitive to warming and water table drawdown [Bridgham et al., 2008]. In warmer and drier manipulations fens became C sources, but bogs continued to function as small sinks though at a reduced rate [Bridgham et al., 1995a; Bridgham et al., 2008].

Changes in peatland biogeochemistry could result from a combination of changes in air temperature (Ta) [Frey and Smith, 2005], precipitation (P) [Robroek et al., 2009] and the concentration of atmospheric CO$_2$ ([CO$_2$]) [Balshi et al., 2009; Heijmans et al., 2001] through changes in net photosynthesis and soil decomposition. However, manipulative field experiments and laboratory incubations can only investigate one or two factors at a time. For example, Robroek et al. (2009) studied the interactive influence of water table and precipitation on the photosynthesis of mosses and pointed out that precipitation should be considered as important as water table. Balshi et al. (2009) simulated the C cycling of boreal forest during the 21st century and they found that boreal forests could function as small C sources to the atmosphere if the interactive changes in CO$_2$ concentration were not considered, but with the inclusion of changes in CO$_2$ concentration the boreal forests still function as a C sink by 2100. Therefore, the non-linear responses of ecosystems to changes in air temperature, precipitation and the concentration of atmospheric CO$_2$ need to be considered together [Luo et al., 2008; Wu et al., 2012].

Our research question is “how sensitive are the C exchanges in northern peatlands to changes in temperature, precipitation and the concentration of atmospheric CO$_2$?” The specific hypotheses that we test are: (1) Bogs and fens respond to changes in climate in a significantly different manner; (2) Bogs can still function as a C sink by 2100 but at a significantly reduced magnitude due to their greater increase in production than ecosystem respiration; (3) Fens may switch to a C source to the atmosphere by 2100, but depending on
the climate change scenarios considered, due to their significantly increased ecosystem respiration; (4) Northern peatlands, as a whole, due to the positive climate change feedback, will reduce their efficiency to absorb the atmospheric C significantly.

In this study, we used a coupled land surface scheme and peatland C model, CLASS3W-MWM [Wu et al., 2012], to simulate the response of C cycling in northern peatlands to the projected changes in climate over the twenty-first century. CLASS3W-MWM was successfully applied to simulate the CO$_2$ fluxes in an ombrotrophic bog, Mer Bleue (MB) in Eastern Canada and a minerotrophic poor fen, Degerö Stormyr (DS) in Northern Sweden under the present climate [Wu et al., 2012]. Here, we used CLASS3W-MWM to simulate the CO$_2$ fluxes at MB and DS under the projected climates simulated by CCCma CGCM3.0 [Flato and Boer, 2001; Kim et al., 2002] for four IPCC emission scenarios (i.e., A1B, A2, B1 and Commit) for 3 time slices (i.e., 2030, 2060 and 2100) of the transient climate simulations.

2 Materials and Methods
2.1 The CLASS3W-MWM framework

In this modelling study, CLASS3W-MWM [Wu et al., 2012] was used to simulate the surface and soil climate and the C cycling in northern peatlands. The land surface scheme, i.e. CLASS3W, was used to simulate the surface and soil climate, including soil temperature (SoilT), soil moisture and water table depth (WTD), based on surface and soil water and energy balance calculation [Wu et al., 2012]. Then, the C cycling component, i.e. MWM [St-Hilaire et al., 2010; Wu et al., 2013], based on the outputs from CLASS3W, was used to simulate the CO$_2$ fluxes such as gross primary production (GPP), total ecosystem respiration (TER), and net ecosystem exchange (NEE) between peatlands and the atmosphere. This model required the following inputs: air temperature, precipitation, wind speed, solar
radiation, specific humidity, and atmospheric pressure and CO₂ concentration.

The details of CLASS3W-MWM were presented in Wu et al. (2012). Here we introduced briefly the overall framework of this model. The hydrological component of CLASS3W-MWM calculated total runoff, including surface overland runoff, subsurface and peatland lateral flow, and groundwater seepage [Verseghy et al., 1991, 1993; Wu et al., 2012]. CLASS3W-MWM solved the energy balance to simulate latent, sensible and ground heat flux. The energy balance and water transport scheme in the soil were calculated to simulate soil temperature and soil moisture for three soil layers, and water table depth [Verseghy et al., 1991, 1993; Letts et al., 2000; Wu et al., 2012]. Then these abiotic variables were used to drive the C cycling component to simulate GPP, TER and NEE, C storage in leaves, stems and roots, one compartment soil C pool, and one fresh litter C pool that decomposed much faster than the soil C pool [St-Hilaire et al., 2010; Wu et al., 2012]. CLASS3W-MWM included three plant functional types (PFT) - shrubs, sedges, and mosses, to represent the vegetation communities in non-treed northern peatlands [Wu et al., 2012, 2013]. We also followed Wu et al. (2012) to spin up the CLASS3W-MWM for our simulation.

### 2.2 Study sites

This modelling study was conducted at two representative peatlands (Table 1): Mer Bleue (MB), an ombrotrophic bog, and Degerö Stormyr (DS), a minerotrophic poor fen. The same parameters and initial values used in Wu et al. (2012) (table 2 in Wu et al. (2012)) were used to configure and initialize for MB and DS respectively to do the C cycle simulation.

We used Mer Bleue (MB), located 10 km east of Ottawa, Ontario, Canada (45.41° N, 75.48° W, 69 m a.m.s.l), as a representative bog in our study. Table 1 presented the details of site characteristics at MB. MB is a 28 km² ombrotrophic bog with dominant vegetation of shrubs and mosses and sparse coverage of sedges (Table 1) [Moore et al., 2002; Lafleur et al., 2003; Roulet et al., 2007]. The peatland area in this study, where the present day input climate data were measured, is only covered by mosses and shrubs. Total aboveground
biomass for vascular species, measured in 1999 and 2004, averaged $356 \pm 100 \text{ g m}^{-2}$ [Moore et al., 2002] and $433 \text{ g m}^{-2}$ [Bubier et al., 2006] respectively. Total belowground biomass, measured in 1999, was $1820 \pm 660 \text{ g m}^{-2}$. Sphagnum capitulum biomass was $144 \pm 30 \text{ g m}^{-2}$ in 1999 [Moore et al., 2002] and $158 \text{ g m}^{-2}$ in 2004 [Bubier et al., 2006].

We used Degerö Stormyr (DS), located in northern Sweden ($64^\circ11'\text{N}, 19^\circ33'\text{E}$), as a representative fen in our study. Table 1 presented the details of site characteristics at DS. DS is an acid, oligotrophic, minerogenic, mixed mire system with an area of $6.5 \text{ km}^2$ and dominant vegetation of sedges and mosses (Table 1) [Sagerfors, 2007; Sagerfors et al., 2008; Wu et al., 2013].

2.3 Climate for simulations
We used the observed climate as the baseline to represent the present climate condition and then adjusted the observations according to the anomalies produced in the simulated climate for the various scenarios. For MB, we used the observation data from January 1 1999- December 31 2006. For DS, we used the observation data from January 1 2001- December 31 2006.

The information on climate change and variability was obtained from the CCCma CGCM3.0 (http://www.cccma.ec.gc.ca/data/cgcm3/cgcm3.shtml). The CCCma CGCM3.0 simulated climate was extracted from the grid cells where MB and DS are located. To derive the information about the climate change and variability, the average air temperature (Ta) and precipitation (P) for 1961-2000 simulated by CCCma CGCM3.0 was used to represent the present average climate state. The climate outputs for 2001-2100 were used to represent the future projected climate states. In this study, we used the climate outputs based on the four IPCC proposed emission scenario – A1B, A2, B1 and Commit. The general characteristics of the four scenarios were shown in Table 2. We chose three time slices – 2030, 2060 and 2100 for this study.

For simulations of the ecosystem model driven by future climate, it was
recommended that future changes from climate model outputs be superimposed on the present mean climate of a reliable present dataset [Clein et al., 2000; McGuire et al., 2008; Balshi et al., 2009]. The changes in Ta and P were imposed on the observation data to represent the changed climate for 2030, 2060 and 2100. So we used an adjusted future climate (equation (1) for temperature and equation (2) for precipitation) to achieve the simulation:

\[ CGCM3_{\text{Adjust}} = \text{Climate}_{\text{Present}} + (CGCM3_{\text{Future}} - CGCM3_{\text{Mean}}), \quad (1) \]

\[ CGCM3_{\text{Adjust}} = \text{Climate}_{\text{Present}} \times \left(\frac{CGCM3_{\text{Future}}}{CGCM3_{\text{Mean}}}\right), \quad (2) \]

where \( CGCM3_{\text{Adjust}} \) was the adjusted future climate for 2030, 2060 and 2100; \( \text{Climate}_{\text{Present}} \) was the present time climate for 1999-2006 for MB and 2001-2006 for DS; \( CGCM3_{\text{Future}} \) was the future projected climate from CGCM3 (e.g. 2030, 2060 and 2100) and \( CGCM3_{\text{Mean}} \) was the mean climate during 1961-2000 also from CGCM3. For the future projected climate from CGCM3, we used the projected monthly output for a single year. The bias corrections represented by \( CGCM3_{\text{Future}} - CGCM3_{\text{Mean}} \) for air temperature and \( CGCM3_{\text{Future}} \div CGCM3_{\text{Mean}} \) for precipitation, were imposed on the present climate for the C simulation. The bias corrections were imposed on the present climate of 1999-2006 for MB, and 2001-2006 for DS. We then ran the model for these 8 or 6 years with the bias correction. The results reported in this paper were the mean of these 8 or 6 years for MB and DS respectively. To extrapolate the monthly outputs from CGCM3 to the required half-hourly climate data, a simple assumption was made that the monthly anomalies derived from CGCM3 were imposed evenly but with a randomly diurnal variation in one month on the half-hourly observed climate data. We imposed the same monthly anomaly on the half-hourly current climate data within the same month, and a random diurnal variation with a mean of zero was imposed to reflect some variation of the half-hourly bias correction. In this simulation, we did not change the probability of extreme weather (e.g. drought and
We adjusted the concentration of the atmospheric CO$_2$ for the three time slices according to the four scenarios using a similar approach to the climate adjustment. However, the difference between the future projected global mean CO$_2$ concentration for the three time slices (Table 2) and the present day global mean CO$_2$ concentration (i.e. 380 ppm) was applied on the half-hour observation of CO$_2$ concentration at MB and DS respectively.

We also used equation (1) and (2) to derive the baseline input climates for CLASS3W-MWM. We calculated the difference between the simulated average climate for 1999-2006 and that for 1961-2000 for MB, and the difference between the simulated average climate for 2001-2006 and that for 1961-2000 for DS. This difference was then imposed on the observed half-hour weather for 1999-2006 for MB, and 2001-2006 for DS respectively to represent the baseline climate data that were used to drive the model for our baseline simulation. We used the CLASS3W-MWM simulated CO$_2$ fluxes based on this baseline climate as our baseline C fluxes for MB and DS respectively. In this paper, our analysis was based on the comparison between the CLASS3W-MWM simulated CO$_2$ fluxes based on the changed climate and those based on the baseline climate.

2.4 Simulation set-up for the transplanted bog and fen and the imposed fen-bog transition

The climate datasets that we used as inputs for CLASS3W-MWM were quite different for the MB bog and DS fen. To determine how much of the difference in response between the bog and the fen in our simulations was due to differences in ecosystem function and how much was due to differences in physical climate we ran the fen with the MB climate (called the transplanted DS fen) and the bog with the DS climate drivers (called the transplanted MB bog). This experiment is somewhat unrealistic because the forms of peatland are partially dependent on climate factors as well as regional geographic factors but it attempts to normalize the effect of climate for the purpose of the comparison of ecological function.
A relatively abrupt fen-bog transition would have major consequences for the C balance in northern peatlands by 2100. The literature on the paleo-ecological succession (e.g. [Kuhry et al., 1993; Hughes et al., 2003]) and contemporary succession in response to disturbance (e.g. [Tahvanainen 2011]) demonstrate rapid reductions in the WTD can induce ombrotrophy – i.e. a transition from a fen to a bog. We examined the simulated WTD for DS fen (Fig. 1) and found that the future DS fen for A1B and A2 would be a good candidate for a fen-bog transition after 2060. Although MWM cannot simulate vegetation dynamics, we forced the model to switch from a fen to a bog vegetation community once the WTD was > 40 cm in the DS fen simulations. In the hybrid fen-bog simulation, once the switch from fen to bog happens, the parameter values of mosses and shrubs for MB were used for the bog simulation (Table 1 in the supplement). We expected that this switch would result in an increase in the moss and/or vascular net primary production (NPP), a change in tissue quality for decomposition, and reduced water stress for vegetation production. From our simulated WTD for DS fen, a possible transition from a fen to a bog occurs for A1B and A2 (Fig. 1). For A2, in the hybrid fen-bog simulation, DS fen will transition to a bog after 2060, hence we carried out a bog simulation with the DS climate for 2060 and 2100. For A1B, a similar transition will occur only by 2100, hence a bog simulation with the DS climate was carried out for 2100. For B1 and Commit, since a WTD > 40 cm was not simulated the original fen simulations remained for the entire period, i.e., 2030, 2060 and 2100. We then examined how the hybrid simulations of the fen-bog transition affected the C balance in northern peatlands by 2100.

3 Results

The temperatures of three soil layers (SoilT1 at 5 cm, SoilT2 at 22.5 cm and SoilT3 at 200 cm: °C) and water table depth (WTD: m below surface) were the simulated physical outputs based on CGCM3.0 derived climate inputs. The simulated surface and soil climate were then inputs to the C cycle simulation where the CO₂ fluxes – GPP, TER and NEE
(NEE=GPP-TER) – between peatlands and the atmosphere were the outputs. In this study, we used NEE to represent the net ecosystem production (NEP) proposed by Chapin III et al. (2006). In this paper, positive NEP indicated C uptake by peatlands, while negative NEP C emission to the atmosphere.

3.1 Changes in environmental variables

For all scenarios except Commit, air temperature (Ta) rose continuously to 2100, though the rate of increase varied slightly among scenarios (Fig. 1). The increase in Ta was larger at DS than at MB, because DS is nearly 20 ° farther north than MB. The increases in Ta in the spring were slightly greater than those in other seasons, while they occurred in all months in all scenarios except Commit (Data shown in the supplement). Most of the increases in monthly Ta were <5.0 °C at MB, and < 4 °C at DS, but increases of >6.0 °C also occurred in the spring season for A1B and A2 at DS, and there was a maximum increase of ~13 °C in the spring for A2 scenario by 2100 at DS (Data shown in the supplement).

The annual changes in precipitation (P) were different at DS than at MB (Fig. 1). The annual P did not show a consistent change among the scenarios. For all scenarios, the annual P was increased (i.e. ΔP>0) to 2100 at MB (Fig. 1: left column). At DS, the annual P increased slightly up to 2100 for A2 and Commit, but for A1B and B1 increased slightly through 2030 to 2060 and then decreased up to 2100 (Fig. 1: right column). Moreover, changes in monthly P were quite variable but the increase and decrease in P existed over all the months (Data shown in the supplement). The increase in P was normally greater in the spring and winter than in the summer and most of the decreases occurred during the growing season (Data shown in the supplement).

In this modelling exercise, soil temperature (soilT), soil moisture and water table
depth (WTD) were simulated through solving the soil energy and water balance. We found that soilT did not consistently increase or decrease over time (Fig. 1). At MB, for all scenarios except Commit, soilT rose up continuously to 2100 by a range of 1-2 °C (Fig. 1: left column). The range of increase in soilT was ~ 1/3 of that for air temperature (Ta). However, at DS, soilT decreased first and then increased by ~1 °C for A2 and increased slightly by < 0.5 °C first and then decreased by < 0.5 °C for all other scenarios (Fig. 1: right column), although Ta increased over time for all scenarios. This phenomenon can be attributed to the non-linear response of soil climate to the changing climate [Wu et al., 2012] that indicated changes in soil climate did not occur consistently or simultaneously with changes in surface climate due to the hydraulic and thermal properties of the peat. For example, the sensitivity analysis of Wu et al. (2012) showed that increasing air temperature resulted in increasing soil water stress, represented by an increase in WTD, which in turn reduced the vegetation photosynthetic capacity. At MB, despite a 200-300 mm increase in annual P, WTD increased only by up to 10 cm by 2100 due to the increase in evapotranspiration, but variation existed among the scenarios. This result was within the magnitude conjectured for peatlands by Roulet et al., (1992b), Bridgham et al. (1995a), Belyea and Malmer (2004), and Bridgham et al. (2008). In contrast to MB, the drop of WTD at DS was much larger in A1B and A2 scenarios - 50 and 70 cm respectively by 2100 (Fig. 1: right column). The changes in WTD with the B1 scenario were similar to that of MB, and there was only a marginal change with Commit scenario.

In CLASS3W-MWM, we used a simple degree-day approach to define the phenology for moss and vascular plants [St-Hilaire et al., 2010]. We calculated the number of days with Ta > 0.0 °C and 4.0 °C to represent the length of growing period for moss and vascular plant respectively (Table 3). For all scenarios except Commit where there was only a marginal varitation over time, the length of growing period for moss and vascular plant increased up to
At MB, the increase for A1B and A2 (45-50 days) was much greater than B1 (~19 days) (Table 3 (a)). Changes in the length of the growing period at DS were not significantly different than those at MB (Table 3), but the changes in Ta at DS, in particular the monthly changes in Ta, were significantly different than those at MB (data shown in the supplement). At DS, the increase for A2 (>85 days) was much larger than for A1B (~45-65 days) and B1 (~40-53 days) (Table 3 (b)).

3.2 CO₂ exchanges

GPP had a significantly different response to changes in climate at DS than at MB. GPP at MB was enhanced by 151-262 g C m⁻² yr⁻¹ up to 2100 for all scenarios except Commit although the magnitude and trend of increase showed a temporal variation among scenarios (Fig. 2: left column). For Commit, GPP experienced only a slight variation over time up to 2100. GPP increased consistently over time to 2100 for A1B and A2, while GPP had a slight decrease to 2060 and then increased to 2100 for B1. However, GPP at DS reduced ~180 g C m⁻² yr⁻¹ by 2100 for A1B and A2 scenarios where the significant changes in the water table occurred (Fig. 2: right column). The drop occurred between 2060 and 2100 for A1B, but after 2030 for A2 scenario. In contrast, GPP increased 30-50 g C m⁻² yr⁻¹ for B1 and Commit by 2100 at DS.

The temporal trend in TER up to 2100 was similar to that of GPP, but the magnitude of increase in TER significantly exceeded that of GPP (Fig. 2). Further, the temporal trend of changes in TER was not consistent over time among scenarios. For all scenarios except Commit, TER at MB was enhanced by 195-291 g C m⁻² yr⁻¹ up to 2100. At DS, A2 showed the largest increase by 2100, but A1B and B1 showed a similar increase of 50-140 g C m⁻² yr⁻¹. For Commit, TER experienced only a slight variation over time up to 2100 at both MB and DS. Among the components of TER (Table 4 (a)), at MB, the largest increase was in autotrophic respiration (AR) (~140-210 g C m⁻² yr⁻¹), followed by oxic decomposition (oxic
HR) (~60-77 g C m$^{-2}$ yr$^{-1}$), and anoxic decomposition (anoxic HR) only increased slightly by 1-3 g C m$^{-2}$ yr$^{-1}$ (Table 4 (a)). At DS, oxic HR was enhanced for all scenarios up to 2100 (Table 4 (b)), but the increase in oxic HR for A1B and A2 with >100 g C m$^{-2}$ yr$^{-1}$ was much larger than the other scenarios with only <50 g C m$^{-2}$ yr$^{-1}$. At DS, both anoxic HR and AR increased and decreased, depending on the scenario of interest, hence when an increase in TER occurred it was primarily attributed to an increase in oxic HR.

NEP, represented by GPP-TER, showed a significantly different temporal trend at DS than at MB. A decrease in NEP occurred in all scenarios by 2100 at both MB and DS because the changes in TER were greater than the changes in GPP. At MB, NEP decreased by ~16-45 g C m$^{-2}$ yr$^{-1}$ by 2100 (Fig. 2: left column), but for all scenarios the bog remained a C sink. However, for A1B and A2, the DS fen switched to a C source (Fig. 2: right column). Further, the changes in NEP were not linear over time. At MB, for A2 and B1, NEP increased by 12-18 g C m$^{-2}$ yr$^{-1}$ by 2060 and dropped after 2060 by 33-52 g C m$^{-2}$ yr$^{-1}$ up to 2100 (Fig. 2: left column). DS switched to a C source for A2 between 2030 and 2060, but this switch only happened after 2060 for A1B. The DS fen remained a C sink for B1.

Climate change did not significantly modify the seasonal patterns of CO$_2$ exchange for mosses and vascular plants up to 2100, but did alter their magnitudes, particularly in the spring for mosses and in the summer for vascular plants (i.e., shrubs and sedges) (Fig. 3 and 4). Moreover, the fen had a slightly different seasonal pattern than the bog due to the differences in changes in seasonal climate (Fig. 3 and 4). At MB, moss GPP increased significantly in the spring and early summer while it decreased slightly in most of the growing season and did not show a significant change in the autumn and winter. However, moss AR showed a slight increase in all seasons (Fig. 3). At DS, moss GPP and AR increased in the spring up to 2100, but did not show significant changes in the winter for both A2 and B1 (Fig. 4). For A2, moss GPP and AR increased slightly up to 2030, but after 2030
dramatically decreased during the growing season. For B1, both moss GPP and AR increased slightly up to 2060 and then decreased slightly during the growing season (Fig. 4). At MB, shrub GPP and AR increased significantly in the growing season, but the magnitude of increase in shrub AR was greater than that in shrub GPP (Fig. 3). Therefore, shrub NPP (GPP-AR) decreased. At DS, for A2, sedge GPP increased slightly in the early summer and decreased slightly in the late summer and fall up to 2030, but after 2030 sedge GPP decreased dramatically during the whole growing season (Fig. 4). For B1, sedge GPP and AR increased slightly up to 2100 during the growing season. Sedge AR did not show a significant difference in the non-growing season for both A2 and B1 (Fig. 4).

The fen had a different response of soil climate to climate changes than the bog (details shown in section 3.1), and this difference translated to different responses of soil respiration to climate changes at the fen than the bog (Table 4, Fig. 3 and 4). Oxic HR increased in all seasons, but the increase in the growing season was significantly greater than other seasons. Accordingly, the changes in NEP also mainly occurred in the growing season (Fig. 3 and 4: bottom boxes). In the non-growing season (mostly winter and spring), NEP did not show significant changes, while NEP showed a significant increase in early summer but a great decrease in late summer and autumn. For A2 at DS, the significant decrease in GPP and the increase in oxic HR resulted in a C loss to the atmosphere during the growing season except in May by 2100, but DS remained a C sink in early summer before 2060 (Fig. 4: bottom box). However, for B1, due to an increase in both moss and sedge GPP, despite the significant increase in oxic HR, DS remained a C sink for the entire growing season up to 2100 (Fig 5: bottom box).

3.3 Simulation results for the transplanted bog and fen and the imposed fen-bog transition

Our simulation for the bog and fen indicated that the fen was more sensitive to future
changes in climate than the bog, but the two peatlands were located in different climatic environments and as a result were subjected to different magnitude of climate change. To assess whether the greater sensitivity of the fen was an inherent functional response, or if it was due to the differences in climate we did a ‘transplant’ experiment: we ran a simulation of DS fen with the bog setting of climate (i.e. the transplanted DS fen) and a bog with the fen setting of climate (i.e., the transplanted MB bog). Note that the transplanted peatlands are being located in climatic and geographic settings that they are not their usual climate – i.e. there are not a lot of temperate fens in southern Ontario nor raised bogs in northern Sweden.

The climatic transplant resulted in a lower (~ 40%) initial NEP of both the transplanted MB bog and transplanted DS fen than their simulated initial NEP with their natural climate (Fig. 5). The transplanted MB bog stayed as a C sink for all scenarios up to 2100 with the exception of A2. For A1B, the CO₂ uptake of the transplanted MB bog by 2100 was significantly reduced. The transplanted DS fen remained a C sink for all scenarios up to 2060, but was a sink only for Commit by 2100. In the three other scenarios the transplanted DS fen switched from a C sink of a similar magnitude to a C source, but the magnitude of the source was only ~50% of the source simulated for the DS fen for A1B and ~25% for A2 in its natural climate setting. These experiments indicate that the simulated fen C balance was more sensitive to climate change than the bog but differences in climate change influenced the magnitude of the changes in C exchanges. Both the simulation based on the natural setting of the bog and the fen, and that based on the transplanted bog and fen suggest that the differences in response of the fen and the bog to climate change are inherently due to the differences in the ecological functions of the fen and the bog.

We configured another scenario of simulations to represent a possible transition from a fen to a bog when a pre-defined hydrological condition was met - i.e., WTD in the fen simulation became >40 cm. A hybrid simulation of the fen-bog transition was carried out for
A1B and A2 after 2060 as these were the only simulations where the changes resulted in a WTD > 40 cm (Fig. 1). Our hybrid simulations showed that C cycling in the fen had a significantly different trajectory if the vegetation transition occurred (Fig. 6). With the vegetation transition the DS peatland continued as a significantly reduced C sink during the entire simulation period for all scenarios except for A2. For A2, the DS peatland only switched to a C source after 2060. Further, this C source was only ~15% of the C source projected for the fen without vegetation change.

4 Discussion

4.1 Climate change in northern peatlands over the twenty first century

The biogeochemistry in northern peatlands is tightly coupled to hydrology [Belyea and Malmer, 2004; Chimner and Welker, 2005; Bridgham et al., 2008; Ise et al., 2008; Robroek et al., 2009]. The hydrology of peatlands is, in turn, determined by local topography, regional climate and the structure and development of the peatland itself [Belyea and Baird, 2006]. Northern peatlands are primarily distributed in high latitudes [Roulet, 2000; Charman, 2002], and climate change is projected to be greater than at lower latitudes [Meehl et al., 2007]. Therefore, the changes in the future climate could lead to changes in C cycling in northern peatlands. Many uncertainties exist on how climate change may impact C cycling in northern peatlands [Moore et al., 1998]. As a result, recent studies have examined peatland C cycling with respects to changes in one or more environmental variables through manipulative experiments - e.g. changes in water table depth and air temperature [Chimner and Cooper, 2003; Chimner and Welker, 2005; Bridgham et al., 2008; Robroek et al., 2009], the concentration of atmospheric CO₂ [Heijmans et al., 2001; Hoosbeek et al., 2001], and/or natural variability through drainage [Strack et al., 2004] or heat waves [Luca, 2008]. However, non-linear interaction exists with warming, increased or decreased precipitation and increased concentration of atmospheric CO₂ [Luo et al., 2008]. Due to physical constraints and temporal scale no manipulative experiments have examined the simultaneous
changes expected with future climate change.

Warmer temperature at high latitudes occurs in all the GCM simulations included in the fourth IPCC report [IPCC, 2007], though the magnitude of the warming varies among models and the SRES emission scenarios (e.g. A1B, A2, B1 and Commit). The projected changes in temperature are less variable than in precipitation [IPCC, 2007]. The models generally suggest an increase in precipitation at high latitudes [Meehl et al., 2007], though the increase is not evenly distributed throughout the year and decreases occur during the growing season in some climate simulations. In our study, the decreases in precipitation during the growing season are much greater for DS, the fen, than MB, the bog. The combination of increased temperature and changes in precipitation leads to a moderately drier bog, but an extremely drier fen in the A1B and A2 scenarios, and these changes have particularly large consequence in the C cycling in the DS fen.

Further, changes in soil climate reflect the combination of changes in energy balance and moisture. However, the changes in soil temperature are much smaller than the changes in air temperature [Wu et al., 2012], suggesting that peatlands are thermally conservative ecosystems [Charman, 2002; Wu et al., 2012].

Changes in temperature and precipitation are not evenly distributed throughout one year [Meehl et al., 2007]. For example, more warming is projected to occur in the winter and spring. This uneven warming pattern is even more salient farther north, as exemplified by DS in this study. However, precipitation does not show a consistent trend among models and SRES emission scenarios [Meehl et al., 2007], for the seasonal distribution of precipitation can change. A decrease in ecosystem moisture and an increase in temperature can have a much more significant effect during the growing season than if these changes occur outside of the growing season. The climate outputs from CGCM3.0 show that warming temperatures are more evenly distributed throughout one year at MB, the bog, than at DS, the fen, as could
be expected because of the further northern location of the DS fen. At MB, the increase in temperature in the spring season (January to April) is slightly larger than other seasons, but the increase in temperature is still significantly larger than in other seasons at DS. This spring season warming (particularly at DS) should influence the phenology of vegetation, in particular mosses, in northern peatlands, and their photosynthesis [Breeuwer et al., 2008a; Breeuwer et al., 2009] and also the decomposition of peat soil [Breeuwer et al., 2008b] through speeding up the soil thawing, enhancing the microbiological activities in peat soil and shortening the duration of snow coverage. The simulations all show a significantly increased growing season and the growth period for mosses that is extended farther than the vascular plants.

4.2 The response of C cycling to climate change in northern peatlands over the twenty first century

Our simulations show that NEP decreases at both bogs and fens because the magnitude of increase in TER exceeds the magnitude of increase in GPP (Fig. 2). The magnitude of decrease in NEP, however, shows a significant difference between bogs and fens. The bog continues to uptake C up to 2100, though the rate of C uptake is reduced by ~16-45 g C m\(^{-2}\) yr\(^{-1}\). The fen, however, switches to a C source up to 2100 for A1B and A2 scenario. Balshi et al. (2009) showed, through a simulation study, that boreal North America still functioned as a C sink at ~ 35 g C m\(^{-2}\) yr\(^{-1}\) up to 2100 for A2 scenario when CO\(_2\) fertilization was included, though northern peatlands were not explicitly parameterized in their study. Our results show that MB bog uptakes ~70 g C m\(^{-2}\) yr\(^{-1}\) in 2100 for A2 and DS fen loses ~200 g C m\(^{-2}\) yr\(^{-1}\) in 2100 for A2. Our modelling result qualitatively agrees with a manipulative field study examined by Bridgham et al (2008). They showed that bogs continued to accumulate C, but fens lost C with warming temperatures and increased water table depth. However, their study did not consider CO\(_2\) fertilization.

Experimental manipulations show that bogs and fens have significantly different C
cycling response to climate change [Weltzin et al., 2000; Weltzin et al., 2003; Strack et al., 2004; Bridgham et al., 2008]. Our simulations also reproduced this different response. The bog GPP increases for all scenarios except Commit, but the magnitude of the increase varies among scenarios. Field studies show that warming in the spring does not alter the onset of vegetation production at MB bog and thus primary production [Moore et al., 2006]. However, our stimulations based on the future projected warming indicate that the increase in bog GPP is attributable to the increase in moss GPP in the spring and shrub GPP in the growing season. Fen GPP decreases for A1B and A2, though moss GPP increases in the spring and increases slightly for B1. The significant decrease in fen GPP is attributable to the decrease in both moss and sedge GPP in the growing season. Our simulations also show that peat soils at the bog and fen have similar responses to climate change. The oxic HR at the bog and fen increases significantly in all seasons, in particular in the growing season.

Our simulations indicate that the fen is more vulnerable to environmental changes than the bog. Bogs have a large range of environmental changes that they tolerate and continue to function reasonably normally as long as environmental changes are not large enough to impose physiological stress on the vegetation. Fens, however, have a narrow tolerance range and therefore tend to change dramatically to environmental changes [Wu et al., 2012]. In our study, the water table in the bog increases only by <10 cm, and both moss and shrub photosynthesis do not show any significantly additional constraints over this range of change. Our results show that moss photosynthesis is not significantly affected during the growing season and moss GPP increases in the spring. However, shrub photosynthesis is enhanced significantly during the growing season. This inconsistent change in moss GPP is because the increases in temperature and the concentration of atmospheric CO₂ have a positive effect on moss production, while the changes in precipitation do not impose an additional constraint on moss water content. Our results agree qualitatively with the field
manipulations that indicated that moss production is unaffected and woody production is enhanced by warming [Weltzin et al., 2000; Weltzin et al., 2003]. However, our results contradict to field CO₂ fertilization experiments which found that elevated CO₂ did not have a significant effect on bog ecosystems [Hoosbeek et al., 2001] because of nutrient poor status, although elevated CO₂ increased the height growth of Sphagnum moss [Heijmans et al., 2001]. However, at present, CLASS3W-MWM does not incorporate nutrient limitations, so plants respond positively to CO₂ fertilization if there is sufficient moisture.

The combined effects of temperature increases, concentration increases of atmospheric CO₂ and a decrease in precipitation have a non-linear impact on the C cycle of the fen. Tuittila et al. (2004) empirically demonstrated a high sensitivity of fen C exchange to changes in water table, while Yurova et al. (2007) simulated with a wetland site version of the LPJ model a similar sensitivity. Our simulations for DS fen indicate that small changes in water table depth result in small changes in GPP, while moderate changes in water table depth lead to large changes in GPP. In CLASS3W-MWM, we use a non-linear function of water table depth to define the water stress for constraining the optimal GPP [Wu et al., 2012, 2013]. Accordingly, the changes in C cycle of the DS fen show a significant difference among the four scenarios in this study because there is a significant difference in changes in water table depth among the four scenarios. For example, for A2, where water table drops by > 40 cm in the summer by 2100, both moss and sedge GPP reduce significantly, but moss GPP increases in the spring. This significant decrease in moss and sedge GPP is because a dramatic increase in temperature in the spring and decrease in precipitation in the growing season results in a large drop of water table depth during the growing season. A water table depth drop below peat surface by > 40 cm [Wu et al., 2012, 2013] significantly increases the water stress on vegetation growth. For B1, where water table has only a marginal change, both moss and sedge GPP do not show significant changes.
In CLASS3W-MWM, we use a simple degree-day approach to define the vegetation phenology [Wu et al., 2012]. Accordingly, the extension or shortening of the growing period responds directly to the changes in temperature, particularly in the spring and autumn. Our results show that moss GPP at the bog and fen are enhanced in the spring. This enhancement indicates that greater warming in the spring results in an earlier onset of vegetation production and thus increases in GPP in the spring. Despite greater warming occurring in the spring at DS fen, the increase in moss GPP at DS fen is not significantly different than at MB bog. This insignificant difference between GPP increases at bogs and fens is because the present-day absolute temperature at DS fen is much lower than at MB bog, and only significantly larger warming can initiate the moss production in the spring at DS fen. However, the warming is not large enough to initiate the production of vascular plant and thus shrub GPP at MB bog and sedge GPP at DS fen do not show any increase in the spring.

In CLASS3W-MWM, AR is simulated as a function of GPP and temperature [Wu et al., 2012]. Accordingly, the changes in AR generally follow the changes in GPP. We use water table depth to define the oxic and anoxic C partitioning of the peat profile [St-Hilaire et al., 2010; Wu et al., 2012, 2013] and peat temperature affects the decomposition rate [St-Hilaire et al., 2010]. Because of the increase in peat temperature and water table, oxic HR generally increases, and in particular during the growing season. In addition, our results show that the rate of oxic HR is normally 1-2 orders of magnitude larger than anoxic HR. Empirical studies inferred that the decomposition rate of oxic peat soil is up to 1000 times larger than that of anoxic peat soil [Clymo et al., 1998; Belyea and Clymo, 2001]. Moreover, AR normally contributes more than 50% to TER in peatlands [St-Hilaire et al., 2010; Wu et al., 2012, 2013]. Therefore, changes in AR and oxic HR generally determine the changes in TER.

Whether peatlands remain as a C sink or switch to a C source is determined by the
balance between primary production (represented by GPP) and decomposition (represented by TER). Matthews et al. (2005) argued that the response of vegetation primary production to climate changes is a critical controlling factor in determining the strength of simulated carbon cycle-climate feedbacks. Our simulation shows that changes in GPP determine the direction of C exchange in northern peatlands. The significant increase in GPP at the bog, resulting from warming temperature and elevated CO₂ concentration, cancels out the dramatic increase in soil decomposition and thus the bog remains as a C sink by 2100, though the strength of C sink is significantly reduced. Contrastingly, the significant decrease in GPP at the fen, resulting from a large drop in water table depth and thus a larger water stress, switches the fen to a C source by 2100 for A1B and A2. The increase in soil decomposition and the decrease in GPP together determine a switch from a C sink to a C source at the fen.

Our study also suggests that only significant increase in GPP can maintain the bog as a C sink for the atmospheric C. This result qualitatively supports the conclusion made by Bridgham et al. (2008) that soil C response of bogs to climate change is determined primarily by plant production and decomposition in the unsaturated zone, i.e. acrotelm.

Based on our simulation study, we conclude that northern peatlands will contribute to a global warming over the twenty first century, considering CO₂ only. Northern peatlands have had a net global cooling effect over the millennial time scale [Frolking et al., 2006; Frolking and Roulet, 2007]. A reduced C sink or switching to a C source means that, all else being equal, the atmosphere will have more CO₂. However, only the extreme changes in A1B and A2 at the fen would amount to an appreciable source of atmospheric CO₂ because peatlands represent a relatively small area (Roulet, 2000). Assuming that northern peatlands are 50% bogs and 50% fens, and all the emitted CO₂ would stay in the atmosphere over the considered period, the A2 scenario amounts to ~ 32 P g C source, equivalent to ~14.5 ppm, to the atmosphere up to 2100. This amount of additional C, if they would stay in the
atmosphere, certainly would be significant. However, all other scenarios would result in < 22 P g C increase of CO₂ to the atmosphere up to 2100. Of course peatlands are not isolated from other components of the terrestrial and oceanic C cycles. So a portion of this excess C would end up in other reservoirs exchanging with the atmosphere. Beyond the short-term only about half the CO₂ would remain in the atmosphere for >5 years (see [Frolking et al., 2006]). Friedlingstein et al. (2006) studied that an extra 50-100 ppm CO₂ would stay in the atmosphere for A2 scenario due to the climate warming feedbacks, although northern peatlands were not considered in their study.

Our simulations were based on the configuration of the bog and the fen in their natural climate setting, but we also examined the response of these two types of peatlands using the same projected climate based on the simulation for the climatically transplanted DS fen and MB bog (Fig. 5). Both simulations show that the fen had a significantly different and greater response to changes in climate than did the bog. Our simulations of the transplanted bog and fen yield similar results but lower magnitude response as are seen for the peatlands in their natural climate setting. Based on the same assumption as used in our original simulations that northern peatlands are 50% bogs and 50% fens, and all the emitted CO₂ would stay in the atmosphere over the considered period, and the transplanted simulations, the A2 scenario amounts to ~38 P g C source, roughly equivalent to a 17 ppm increase in atmospheric CO₂ in 2100. All other scenarios result in < 25 P g C release up to 2100. This result, derived from the transplanted bog and fen, combined with our result derived from the natural setting of the bog and the fen, suggest that northern peatlands can provide a significant feedback between global C cycling and climate change.

In this study, we imposed a transition from fen vegetation to bog vegetation when WTD of a fen increased to >40 cm on MWM. We did not impose the same vegetation change to CLASS3W because in our version it was not possible [Wu et al., 2012]. Our hybrid
simulation of the fen-bog transition resulted in the DS fen-bog remaining a small sink except only in the 2100 simulations for A2 (Fig. 6). Our back-of-envelope calculation based on the hybrid simulation with an imposed fen-bog transition shows that A2 became an $-14 \text{ P g C}$ source, which is less than half of the amount of the C source projected by our results derived from the natural setting of the bog and the fen, and the transplanted bog and fen. This result implies that a possible fen-bog transition with a vegetation change would significantly reduce the affect of climate change on the C balance of northern peatlands in the 21st century. Therefore, it is critical to take into account the possible fen-bog transition and its associated vegetation dynamics in future model development when examining the impacts of the projected climate change on the C cycling of northern peatlands, particularly for the extreme scenario of climate change, such as A1B and A2.

Our research suggests that some northern peatlands could experience a dramatic change in C cycling due to climate change, while other may not. Whether a northern peatland continues to function as a C sink or switch to a C source largely depends on the type of peatland and climate change scenario considered. Our simulation study also concludes that northern peatlands will contribute to a global warming over the twenty first century due to its reduced capacity of absorbing the atmospheric C resulted from the positive feedback to the projected climate change. If northern peatlands were considered in the carbon cycling-climate feedback, there would be an additional increase of the atmospheric CO$_2$ concentration by 10-14 ppm for the worst climate change scenarios. This increase is certainly not insignificant. Therefore, we highly urge that northern peatlands be included in the C-coupled climate model to fully understand the response of C cycling in terrestrial ecosystems to climate change and reduce the uncertainties for projecting the future climate.

4.3 Uncertainties and limitation

This study represents one of the first attempts to examine the sensitivity of the net ecosystem productivity of northern peatlands to the projected changes in climate over the
twenty first century. Even though we believe this work represents a significant progress, we acknowledge that there are a number of significant uncertainties and limitations that need to be addressed in our further studies.

Firstly, CLASS3W-MWM assumes fixed vegetation. There is no change in plant community structure with changes in environmental variables. However, plant communities in peatlands change when there are, in particular, significant changes in moisture [Weltzin et al., 2000; Weltzin et al., 2003], especially at a wet site, e.g. poor fen or rich fen [Strack et al., 2004]. With changes in wetness, the competition status between mosses and vascular vegetation in northern peatlands is modified as well [Breeuwer et al., 2008a; Breeuwer et al., 2009]. Over a long period of time vegetation succession is from graminoid fens to shrub or tree-dominated plant communities with a lower water table depth, which leads to a greater C accumulation in both soil and plant biomass in northern fens [Weltzin et al., 2000; Weltzin et al., 2003].

Another limitation is that CLASS3W-MWM is a one dimensional model. This one dimensional framework indicates that only vertical exchanges in water, energy and C are considered. Lateral outflow is simulated by CLASS3W-MWM for bogs [Wu et al., 2012], but there is no internal redistribution of water. In many peatlands, this lateral distribution is important to the development of micro and meso-topography [Baird et al., 2009] and can lead to considerable heterogeneity. In addition, CLASS3W-MWM currently does not have lateral link with groundwater. This simplification is not a serious drawback for the simulation of bogs because they are ombrotrophic- i.e. rainfed [Charman, 2002], but it imposes a large uncertainty for the fen systems that receive additional water and possibly nutrients from the surface and groundwater sources [Charman, 2002; Rydin and Jeglum, 2006]. Therefore, with the omission of the horizontal linkage between peatlands and surrounding uplands, especially for water exchange, we cannot properly simulate the water table depth for a fen. We likely
overestimated the reduction of water table depth leading to an overestimation of the magnitude of C loss at the fen.

The MWM is one-directionally coupled to CLASS3W. This one-way coupling limits our study because the hydrological and biophysical variables are passed from CLASS3W to the MWM, but the ecosystem attributes are not passed back to CLASS3W.

This study did not include nitrogen (N) cycling, which is also a significant limition and potential source of error. The slow rate of plant production and soil decomposition in northern peatlands is, in part, attributed to the low nutrient availability [Basiliko et al., 2006]. Changes in N availability, possibly resulted from the changes in atmospheric N deposition and soil microbial activity [Basiliko et al., 2006; Bragazza et al., 2006; Gunnarsson et al., 2008], alter the rate of soil decomposition and vegetation production in northern peatlands [Bridgham and Richardson, 2003; Bragazza et al., 2006; Breeuwer et al., 2008b; Gunnarsson et al., 2008; Breeuwer et al., 2009].

To examine the net changes in peatland climate feedbacks CH$_4$ needs to be simulated because whether a peatland is contributing to a net warming or a net cooling is a result of a combined effect of changes in net CO$_2$ sequestration and net CH$_4$ emission [Frolking et al., 2006; Frolking and Roulet, 2007]. Additionally, the loss of C by dissolved organic carbon (DOC) export should also be examined.

Lastly, this study does not take into account the potential impacts of any natural and human disturbances on the C cycling in northern peatlands, such as fire [Page et al., 2002; Randerson et al., 2006; Turetsky et al., 2011 a, b].

Acknowledgements

NTR received support for the development and evaluation of MWM and CLASS3W from a Canadian Foundation for Climate and Atmospheric Sciences research network (Canadian Global Coupled Climate Carbon Modelling) and a Natural Science and
Engineering Research Council of Canada Discovery Grant. JW would like to thank the funding support from Grenfell Campus’s start-up fund, Vice-President Research Fund, Humber River Basin Project fund, Agricultural Research Initiative of NL, and Research & Development Corporation of NL’s Ignite R&D. We would like to thank the editor and the two anonymous reviewers for their comments and suggestion that we believe have improved our manuscript considerably.

References


Nilsson, M., Sagerfors, J., Buffam, I., et al., 2008. Contemporary carbon accumulation in a boreal oligotrophic minerogenic mire - a significant sink after accounting for all C-


Table 1: The site characteristics and the 40-year (1961-2000) average climate of the study sites, i.e. Mer Bleue (MB) representing a bog, and Degerö Stormyr (DS) representing a fen.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Bog (MB)</th>
<th>Fen (DS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Mer Bleue</td>
<td>Degerö Stormyr</td>
</tr>
<tr>
<td>Climate</td>
<td>Cool continental temperate</td>
<td>Cold temperate humid</td>
</tr>
<tr>
<td>Nutrients</td>
<td>Poor</td>
<td>Rich</td>
</tr>
<tr>
<td>Water sources</td>
<td>Precipitation</td>
<td>Precipitation, surface runoff and groundwater</td>
</tr>
<tr>
<td>Depth of peat</td>
<td>5-6m</td>
<td>3-4m</td>
</tr>
<tr>
<td>Basal age</td>
<td>~9000 yrs</td>
<td>~8000 yrs</td>
</tr>
<tr>
<td>Mean annual air temperature (°C)</td>
<td>6.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Days above 0 °C</td>
<td>206.0</td>
<td>150.0</td>
</tr>
<tr>
<td>Mean annual precipitation (mm)</td>
<td>943</td>
<td>523</td>
</tr>
<tr>
<td>Precipitation as snow (mm)</td>
<td>235.0</td>
<td>233.0</td>
</tr>
</tbody>
</table>
Table 2: The general characteristics for the four IPCC emission scenarios chosen in this study and the global mean warming from multi-model (CCCma CGCM3.0 was included) ensemble mean for four time periods relative to 1980-1999 for each of the 4 scenarios [IPCC, 2007].

Note: [CO$_2$]: the concentration of atmospheric CO$_2$.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>A1B</th>
<th>A2</th>
<th>B1</th>
<th>Commit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic growth</td>
<td>Very rapid</td>
<td>Very heterogeneous with local identity</td>
<td>Medium</td>
<td>Commit to reduce GHG</td>
</tr>
<tr>
<td>Technological development</td>
<td>Rapid</td>
<td>Slow</td>
<td>Medium</td>
<td>Commit to reduce GHG</td>
</tr>
<tr>
<td>Global convergence</td>
<td>Slow</td>
<td>Slow</td>
<td>Fast</td>
<td>Fast</td>
</tr>
<tr>
<td>Energy use</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Environmental sustainability</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Global population</td>
<td>Peak in mid-century</td>
<td>15 billion by 2100</td>
<td>Same as A1B</td>
<td>N/A</td>
</tr>
</tbody>
</table>

[CO$_2$] (ppm)

<table>
<thead>
<tr>
<th>Present-day</th>
<th>2030</th>
<th>2060</th>
<th>2100</th>
<th>Present-day</th>
<th>2011-2030</th>
<th>2046-2065</th>
<th>2080-2099</th>
<th>2180-2199</th>
</tr>
</thead>
<tbody>
<tr>
<td>[CO$_2$] (ppm)</td>
<td>380</td>
<td>460</td>
<td>570</td>
<td>720</td>
<td>0.00</td>
<td>0.69</td>
<td>1.75</td>
<td>2.65</td>
</tr>
<tr>
<td>2060</td>
<td>380</td>
<td>450</td>
<td>580</td>
<td>800</td>
<td>0.00</td>
<td>0.64</td>
<td>1.65</td>
<td>3.13</td>
</tr>
<tr>
<td>2010</td>
<td>380</td>
<td>440</td>
<td>500</td>
<td>550</td>
<td>0.00</td>
<td>0.66</td>
<td>1.29</td>
<td>1.79</td>
</tr>
<tr>
<td>2046-2065</td>
<td>0.00</td>
<td>0.64</td>
<td>1.29</td>
<td>1.79</td>
<td>0.00</td>
<td>0.37</td>
<td>0.47</td>
<td>0.56</td>
</tr>
<tr>
<td>2080-2099</td>
<td>1.75</td>
<td>1.65</td>
<td>1.29</td>
<td>1.79</td>
<td>0.00</td>
<td>0.37</td>
<td>0.47</td>
<td>0.56</td>
</tr>
<tr>
<td>2180-2199</td>
<td>2.65</td>
<td>3.13</td>
<td>1.79</td>
<td>2.10</td>
<td>0.00</td>
<td>0.37</td>
<td>0.47</td>
<td>0.56</td>
</tr>
</tbody>
</table>
Table 3: The number of days with daily $\text{Ta} > 0.0^\circ\text{C}$ and $\text{Ta} > 4.0^\circ\text{C}$ for the baseline, 2030, 2060 and 2100 for the four selected scenarios in this study: (a) for MB; (b) for DS.

(a) MB

<table>
<thead>
<tr>
<th></th>
<th>A1B(&gt;0.0)</th>
<th>A1B(&gt;4.0)</th>
<th>A2(&gt;0.0)</th>
<th>A2(&gt;4.0)</th>
<th>B1(&gt;0.0)</th>
<th>B1(&gt;4.0)</th>
<th>Commit(&gt;0.0)</th>
<th>Commit(&gt;4.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>255</td>
<td>209</td>
<td>255</td>
<td>209</td>
<td>255</td>
<td>209</td>
<td>255</td>
<td>209</td>
</tr>
<tr>
<td>2030</td>
<td>257</td>
<td>226</td>
<td>272</td>
<td>241</td>
<td>276</td>
<td>235</td>
<td>264</td>
<td>225</td>
</tr>
<tr>
<td>2060</td>
<td>291</td>
<td>257</td>
<td>286</td>
<td>247</td>
<td>281</td>
<td>236</td>
<td>253</td>
<td>214</td>
</tr>
<tr>
<td>2100</td>
<td>301</td>
<td>269</td>
<td>304</td>
<td>268</td>
<td>274</td>
<td>238</td>
<td>270</td>
<td>229</td>
</tr>
</tbody>
</table>

(b) DS

<table>
<thead>
<tr>
<th></th>
<th>A1B(&gt;0.0)</th>
<th>A1B(&gt;4.0)</th>
<th>A2(&gt;0.0)</th>
<th>A2(&gt;4.0)</th>
<th>B1(&gt;0.0)</th>
<th>B1(&gt;4.0)</th>
<th>Commit(&gt;0.0)</th>
<th>Commit(&gt;4.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>207</td>
<td>160</td>
<td>207</td>
<td>160</td>
<td>207</td>
<td>160</td>
<td>207</td>
<td>160</td>
</tr>
<tr>
<td>2030</td>
<td>228</td>
<td>179</td>
<td>222</td>
<td>171</td>
<td>237</td>
<td>183</td>
<td>214</td>
<td>165</td>
</tr>
<tr>
<td>2060</td>
<td>276</td>
<td>219</td>
<td>251</td>
<td>194</td>
<td>226</td>
<td>176</td>
<td>203</td>
<td>163</td>
</tr>
<tr>
<td>2100</td>
<td>272</td>
<td>208</td>
<td>303</td>
<td>248</td>
<td>260</td>
<td>200</td>
<td>222</td>
<td>170</td>
</tr>
</tbody>
</table>
Table 4: The CLASS3W-MWM simulated components of TER (AR: autotrophic respiration; oxic HR (OHR): oxic decomposition; anoxic HR (AHR): anoxic decomposition; HR (heterotrophic respiration =oxic HR+anoxic HR) at MB (a) and DS (b) for Baseline, 2030, 2060 and 2100 for A1B, A2, B1 and Commit respectively.

Note: TER=AR+HR. The unit is g C m\(^{-2}\) yr\(^{-1}\).

(a) MB

<table>
<thead>
<tr>
<th></th>
<th>A1B</th>
<th>A2</th>
<th>B1</th>
<th>Commit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>37</td>
<td>123</td>
<td>12</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>123</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td>2030</td>
<td>45</td>
<td>137</td>
<td>12</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>137</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>2060</td>
<td>51</td>
<td>179</td>
<td>14</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>179</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>2100</td>
<td>58</td>
<td>197</td>
<td>15</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>197</td>
<td>15</td>
<td>1</td>
</tr>
</tbody>
</table>

(b) DS

<table>
<thead>
<tr>
<th></th>
<th>A1B</th>
<th>A2</th>
<th>B1</th>
<th>Commit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>299</td>
<td>101</td>
<td>20</td>
<td>299</td>
</tr>
<tr>
<td></td>
<td>299</td>
<td>101</td>
<td>20</td>
<td>299</td>
</tr>
<tr>
<td>2030</td>
<td>333</td>
<td>128</td>
<td>21</td>
<td>335</td>
</tr>
<tr>
<td></td>
<td>333</td>
<td>128</td>
<td>21</td>
<td>335</td>
</tr>
<tr>
<td>2060</td>
<td>342</td>
<td>170</td>
<td>16</td>
<td>348</td>
</tr>
<tr>
<td></td>
<td>342</td>
<td>170</td>
<td>16</td>
<td>348</td>
</tr>
<tr>
<td>2100</td>
<td>251</td>
<td>209</td>
<td>7</td>
<td>274</td>
</tr>
<tr>
<td></td>
<td>251</td>
<td>209</td>
<td>7</td>
<td>274</td>
</tr>
</tbody>
</table>
Fig. 1: The CGCM3.0 simulated climate (Ta (°C): air temperature; P (mm): precipitation) and
the CLASS3W-MWM simulated soil climate (soil temperature of three soil layers (°C):
SoilT1, SoilT2 and SoilT3; WTD (m): water table depth (below surface)) for baseline, 2030,
2060 and 2100 respectively.

The left column is for Mer Bleue (MB) and the right column for Degerö Stormyr (DS).
From top to bottom are for A1B, A2, B1 and Commit respectively.
Fig. 2: The CLASS3W-MWM simulated CO₂ fluxes (gross primary production (GPP), total ecosystem respiration (TER) and net ecosystem production (NEP)) at MB (the left column), and DS (the right column) for 2030, 2060 and 2100 for A1B, A2, B1 and Commit respectively. The baseline run is represented by a horizontal dashed line across each panel. From top to bottom are for GPP, TER and NEP respectively. The unit is g C m⁻² yr⁻¹.
Fig. 3: The monthly C fluxes for 2030, 2060 and 2100 at MB. Left column is for A2 and right for B1.

From the top to bottom are for moss GPP, shrub GPP, moss AR, shrub AR, oxic HR and NEP. The unit is g C per m² per month. The monthly baseline C fluxes are embedded by the solid curve with dots.
Fig. 4: The monthly C fluxes for 2030, 2060 and 2100 at DS. Left column is for A2 and right for B1.

From the top to bottom are moss GPP, sedge GPP, moss AR, sedge AR, oxic HR and NEP. The unit is g C per m$^2$ per month. The monthly baseline C fluxes are embedded by the solid curve with dots.
Fig. 5: The CLASS3W-MWM simulated NEP for the transplanted bog (i.e., MB bog with DS climate, called the transplanted MB bog) and fen (i.e., DS fen with MB climate, called the transplanted DS fen), and their comparison with the CLASS3W-MWM simulated NEP for the bog and fen with their natural climate settings (i.e., MB bog and DS fen). The simulated NEP is shown for 2030, 2060 and 2100 for A1B, A2, B1 and Commit respectively. The baseline run is represented by a horizontal dashed line across each panel. The unit is g C m$^{-2}$ yr$^{-1}$.
Fig. 6: The CLASS3W-MWM simulated NEP for the DS peatland based on the hybrid simulation of a fen-bog transition where DS fen is forced to transit to a bog when WTD increases to >40 cm (Top column), and a DS fen simulation with its natural setting where DS always stays as a fen during the whole simulation period (Bottom column). The simulated NEP is shown for 2030, 2060 and 2100 for A1B, A2, B1 and Commit respectively. The baseline run is represented by a horizontal dashed line across each panel. The unit is g C m$^{-2}$ yr$^{-1}$. 

©2014 American Geophysical Union. All rights reserved.