Simulating northern peatland-atmosphere carbon dioxide exchange with changes in climate

Jianghua Wu

Department of Geography
McGill University
Montreal, Quebec, Canada
August 2009

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Doctor of Philosophy

Abstract

About half of the global wetlands are located between 50-70° N, where climate change is projected to be greater than other regions. More than 95% of northern wetlands are peatlands. The majority of peatlands accumulate soil carbon (C) because, on average, net primary production (NPP) exceeds decomposition. Peatlands store ~ 450 G t soil carbon (1Gt C=10^{15} g C), a mass equivalent to about 20% of global terrestrial soil C, or half of atmospheric C. The carbon exchange between peatlands and the atmosphere is sensitive to climate variability and change because of the tight coupling with hydrology and ecosystem biogeochemistry. A critical question of this thesis is "Will northern peatlands continue to function as C sink under the projected climate change?"

I use a modelling approach to answer this question. Firstly, a peatland C cycling model, the McGill Wetland Model (MWM), originally developed to simulate the C dynamics of ombrotrophic bogs, was modified, parameterized and evaluated for the simulation of the CO_2 biogeochemistry of fens. Three modifications were made: (1) a function describing the impact of soil moisture on the optimal gross primary production (GPP); (2) a scheme to partition the peat profile into oxic and anoxic C compartments based on the effective root depth as a function of daily sedge NPP; and (3) a modified function describing the fen moss water dynamics. Secondly, I have examined the effect of bog microtopography on the simulation of ecosystem-level C cycling and found model processes scale linearly, so "parameter" upscaling can be used in regional scale assessments. Thirdly, I successfully evaluated a coupled Wetland version of Canadian Land

Surface Scheme (CLASS3W) and MWM (called CLASS3W-MWM) for bogs and fens. The sensitivity analysis indicates that northern peatlands are thermally and hydrologically conservative and the combination of changes in temperature, precipitation and double CO_2 concentration is much different than the sensitivity of peatlands to each environmental variable on their own. Finally, I used CLASS3W-MWM to do a first-order experiment on how the CO_2 exchange in northern peatlands might change under the changing climate. For future climate, I adjusted the site "measured" climate variables by the climate anomalies estimated by the CCCma-GCM3.0 for three time slices (2030, 2060 and 2100) using four different climate scenarios (A1B, A2, B1 and Commit). These simulations showed that bogs and fens have significantly different responses to climate change, particularly that fens are more sensitive to environmental change than bogs. At 2100, the bog remains a C sink for all the climate scenarios assessed because a significant increase in GPP still offset, to a smaller extent, the large increase in total ecosystem respiration (TER). However, by 2100, the fen switches to a C source for two scenarios (A1B and A2), due to a dramatic decrease in GPP and a significant increase in TER resulting from water stress linked to a large drop of water table depth.

Résumé

Environ la moitié de l'ensemble des tourbières sont situées entre 50-70° N, là où les changements climatique prévus risquent d'être plus important que dans les autres régions. Plus de 95% des milieux humides nordiques sont des tourbières. La majorité des tourbières accumule du carbone (C) puisqu'en moyenne, la production nette primaire (NPP) excède la décomposition. Les tourbières accumulent environ 450 G t de C (1Gt C=10^{15} g C), une masse équivalente à environ 20% du C terrestre, ou la moitié du C atmosphérique. L'échange de C entre les tourbières et l'atmosphère est sensible aux changements climatiques et varie en fonction du lien entre leur hydrologie et la biogéochimie de l'écosystème. Une des questions critiques de cette thèse est « est-ce que les tourbières du nord demeureront des puits de C malgré les changements climatiques projetés? ».

J'utilise une approche de modélisation pour répondre à cette question. Premièrement, le modèle représentant le cycle du C dans les tourbière, le *McGill Wetland Model (MWM)*, développé à l'origine pour simuler la dynamique du C dans les tourbières ombrotrophiques, a été modifié et les paramètres ajustés et évalués afin de simuler la biogéochimie du dioxide de carbone (CO_2) des tourbières oligotrophiques. Trois modifications ont été faites : (1) une fonction décrivant l'impact de l'humidité du sol sur la production primaire brute (GPP) optimale; (2) un schéma pour partitionner le profil de la tourbière selon les compartiments oxiques et anoxiques du C basé sur la profondeur effective des racines en fonction de la NPP journalière du carex; et (3) une fonction modifiée

décrivant la dynamique de l'eau de la tourbe en milieu oligotrophique. Deuxièmement, j'ai examiné l'effet de la microtopographie de la tourbière sur la simulation du cycle du C à l'échelle de l'écosystème et trouvé les processus du modèle à l'échelle linéaire, pouvant ainsi modifier les paramètres en changeant l'échelle utilisée pour l'évaluation à l'échelle régionale. Troisièmement, j'ai évalué avec succès une version couplée du modèle *Canadian Land Surface Scheme (CLASS3W)* et *MWM*, nommé (CLASS3W-MWM) pour les types de tourbières ombrotrophiques et oligotrophiques. L'analyse de sensibilité indique que les tourbières du nord sont conservatrices au niveau thermal et hydrologique et la combinaison du changement de température, de précipitation et une double concentration de CO_2 est très différente par rapport à la sensibilité de chaque variable individuellement.

Finalement, j'ai utilisé le CLASS3W-MWM pour faire une expérience de premièr-ordre vérifiant comment l'échange de CO_2 dans les tourbières du nord peuvent être modifiés sous un climat changeant. Pour les climats futurs, j'ai ajusté la variable climatique du site « mesuré » par les anomalies climatiques estimées par le CCma-GCM3.0 pour trois périodes de temps (2030, 2060 et 2100) en utilisant quatre différents scénarios climatiques (A1B, A2, B1 et Commit). Ces simulations ont montré que les tourbières oligotrophiques et ombrotrophiques ont des réponses significativement différentes aux changements climatiques, particulièrement les tourbières oligotrophiques, qui sont plus sensibles au changements environnementaux que les tourbières ombrotrophiques. En 2100, la tourbière ombrotrophique demeure un puits de C durant la totalité du scénario puisqu’une augmentation significative de la GPP compensait toujours, même si de manière moindre, l’augmentation importante de la respiration de l’écosystème (TER). Toutefois, en 2100, la tourbière oligotrophique est devenue une source de C pour deux scénarios (A1B et A2), dû à une diminution drastique de la GPP et une augmentation du TER résultant du stress hydrique lié à une grande diminution de la profondeur de la nappe phréatique.

Acknowledgement

Throughout the five years of my PhD studies at McGill University, many people have helped me and I would like to give my sincere thanks to them. I would also apologize in advance to those that I have missed.

Above all, I would like to give my most sincere thanks to my Ph.D supervisor, Prof. Nigel T. Roulet for his continuous encouragement, support, and guidance throughout my PhD studies at McGill University. I would also like to thank him for providing me with excellent financial support. I attribute all of my academic achievements, if any, to him. His academic insight and creative thinking have shaped my dissertation topics and led me all the way through. He has encouraged me to always think a bit harder and more deeply and go a little further to places where nobody else has gone yet. To the point where my thesis is in its final form, Nigel has reviewed and commented thoroughly on my thesis. More importantly, he has always been available to provide any help that I needed. Not only has he given me the cutting-edge knowledge but also the unique academic tools with which I will use for my academic career all my life. Not only have I benefited from him in the academic field but also his characteristic charm and his research attitudes have influenced me and set a role model for me. He is such an important mentor, friend and elder to me.

A special thank is given to Dr. Tim R. Moore for his encouragement, helps, support and comments on my studies. I would like to thank my other doctoral supervisory committee members for their discussion and comments for my research: Dr.Navin Ramankutty, Dr. Changhui Peng, and Dr. Jonathan Seaquist.

I would also like to thank Dr. Peter Lafleur and Dr. Elyn Humphreys who have supported me with the data. Thanks to Dr. Steve Frolking and Dr. Ian Strachan for their comments and discussion on my research.

Thanks are given to Dr. Sebastien Breau, Dr. Renee Sieber, Dr. Bernhard Lehner, Dr. Garry Peterson and Mrs. Catherine Moore for whom I have worked as a TA and from whom I have also learnt so much. Thanks to Dr. Lea Berrang Ford for providing me with the lab space. I would also like to specially thank Mrs Cathy Roulet for her warm and kind help in various aspects during the five years.

I also would like to thank all of the professors that I met during my one-month visit in Sweden. Special thanks to Dr. Mats Nilsson and Dr. Jorgan Sagerfors who have given me such supportive cooperation and facilitated my stay in Umeå , SLU, Sweden. I would also like to thank Dr. Almut Arneth and Dr. Guy Schurgers for inviting me to give a talk in Lund University, supporting my stay and discussing my research. Mr. Francois St-Hilaire is sincerely thanked for generously offering the code of the original MWM. Dr. Ouyang Bin is specially thanked for providing me with the CLASS3W.

My special thanks are also given to Dr. Bernard Bauer, Mrs. Bea Bauer and Dr. John Wilson for supporting my study at the University of Southern California. Dr. Alain Tremblay is specially thanked for providing supports for my visit to EM-1 reservoir in Northern Quebec.

I would like to specially thank Dr. Dolly Kothawala and Ms. Olivia Yu for proofreading my thesis and Dr. Julie Turgeon for translating my abstract to French. Special thanks are also given to Ms. Jin Feng and Mr. Chen Gai for proofreading the citation and bibliography of my thesis.

I would like to thank my fellow graduate students in Professor Roulet’s crew: Dr. April James, Dr. Nicola McEnroe, Ms. Julie Talbot, Mr. David Olefeldt, Mr. Young Il Kim, Mr. Derrick Lai and Ms. Angela Kross. It has all been my pleasure and honour to work with all of current and former “lab group-rats”. I would like to thank the following colleagues for their support, discussion and kindness: Ms. Meaghan Murphy, Mr. Mike Dalva, Dr. Christian Abizaid, Dr.

James John Luce, Dr. Oliver Sonnentag, Dr. Andreas Persson, Dr. Weimin Ju, Dr. Haibin Wu, Dr. Dong Hua, Dr. Xiaolu Zhou, Dr. Xiyuan Chen, Dr. Fengmin Yuan, Dr. Shuhua Yi, Dr. Jingfeng Sheng, Dr. Yang Shao, Mr. Jianfeng Sun, Ms. Julia Christensen, Ms. Heidy Zunn, Mr. Michael Rubinstein, and Mr. David Oswald. I would also like to thank Ms. Maria Marcone, Ms. Pauline Nesbitt, Ms. Paula Kestelman, Mr. Joseph Vacirca, Ms. June Connolly, and Ms. Ruilan Shi for making my life much easier at the Geography Department of McGill University.

I would like to thank Global Environment and Climate Change Centre (GEC3) for supporting my visit to Umeå, SLU in Sweden and other conference trips, and Fluxnet-Canada research network (FCRN) (now Canada Carbon Program, CCP) for funding me to attend several conferences.

I would like to specially thank all my family members in China who have given me unlimited love, encouragement and support. Special thanks are given to my older sister, Wu Fengling, for her love and her sacrifice to always support my studies. Thanks are also given to my family members in Ireland who always love us and support us. Last but not least, I must specially thank my wife, Ning Wang, for her everlasting love, support, patience, encouragement and understanding. Finally, thanks to my sweetheart Luis (Ruiqian) for the happiness and joyful time he has brought to me.

Contribution statement

Chapter 3: Six years simulation of carbon fluxes for a minerotrophic mire (poor fen) in Northern Sweden using the McGill Wetland Model (MWM)

Jianghua Wu (JW), under the supervision of Nigel T. Roulet (NTR), designed this research and JW conducted it and analyzed the results. JW wrote this manuscript and received comments from NTR and Mats Nilsson (MN). Jorgen Sagerfors provided the input data for running MWM simulations.

Chapter 4: Does microtopography really matter in modelling ecosystem level carbon cycling of an ombrotrophic bog?

JW, under the supervision of NTR, designed this research and JW conducted it and analyzed the results. JW wrote the manuscript and NTR and Peter Lafleur (PL) provided comments. PL and Elyn Humphreys (EH) provided the surface weather and soil climate data for hummocks and hollows and the observed C fluxes from the eddy-covariance tower at Mer Bleue (MB). Tim Moore provided some of the initialization data and parameters for the MWM for hummock and hollows.

Chapter 5: Simulating the carbon cycling of northern peatlands using a coupled land surface climate and wetland carbon model (CLASS3W-MWM)

JW, under the supervision of NTR, designed this research and JW conducted it and analyzed the results. JW wrote this manuscript and NTR provided comments.

Chapter 6: Northern peatlands still function as carbon sinks, but can switch to carbon sources as well under the changing climate up to 2100

JW, under the supervision of NTR, designed the research and JW conducted it and analyzed the results. JW wrote this manuscript and NTR provided comments.

Table of contents

List of figures

List of tables

Chapter 1 Introduction

Since the industrial revolution, the atmospheric concentration of greenhouse gases (GHGs) has been continuously increasing at a much higher rate than pre-industrial period. For example, the global atmospheric concentration of CO_2 has increased from a pre-industrial level of about 280 ppm to 379 ppm in 2005; the global atmospheric concentration of methane (CH_4) has increased from a pre-industrial level of about 715 ppb to 1774 ppb in 2005; the global atmospheric concentration of nitrous oxide has increased from a pre-industrial level of 270 ppb to 319 ppb in 2005 (IPCC, 2007). Increasing atmospheric greenhouse gas concentration has resulted in changes in atmospheric circulation and global climate (IPCC, 2007). The increasingly intensified human activities, primarily the burning of fossil fuels and the changes in land use (Houghton, 1999; DeFries *et al.*, 2002; Lewis, 2006), are believed to be major contributors to the increasing atmospheric concentrations of greenhouse gases (IPCC, 2007). The global source of CO_2 from fossil fuel burning and tropical deforestation is about 7.3-9.2 G t C yr^{-1} (1 G t C=10^{15} g C). Only half of this C (*i.e.* 3.6-4.0 G t C yr^{-1}), however, remains in the atmosphere (Gifford, 1994; Sarmiento and Gruber, 2002; IPCC, 2007). The other half has been absorbed by the "surface" sinks in the land biosphere or oceans (Gifford, 1994). Oceans uptake about 1.3-2.9 G t C yr^{-1}, and the rest so-termed "missing sink" should be attributed to terrestrial ecosystems (Gifford, 1994; Houghton *et al.*, 1998; Schindler, 1999; IPCC, 2007). As a result, much attention has been directed to researching the terrestrial global C cycle for finding this unidentified terrestrial sink and determining the responsible mechanisms (Schimel *et al.*, 2001; IPCC, 2007).

Large uncertainties are associated with the estimate of this “missing” terrestrial C sink, due to a lack of knowledge on the spatial and temporal terrestrial C sources and sinks along with human and natural disturbances to terrestrial ecosystems. It is still puzzling where the C sinks are located. Significant C sinks have been recognized to occur in extratropical regions, especially boreal and temperate forests (Schimel *et al.*, 2001). With more anthropogenic greenhouse gases being emitted into the atmosphere, a big remaining question for the global C cycle is “where do the GHGs go and how much will stay in the atmosphere?” Moreover, terrestrial C cycling has been recognized as a key area of uncertainty for predicting the future climate (Huntingford *et al.*, 2009). To reduce this uncertainty, studies are required to develop a deep and systematic understanding how different natural ecosystems (for example, boreal forest and peatlands) respond to natural and human disturbance. One of the key questions is “how will the C cycling of natural ecosystems respond to the future climate change and variability?”.

Over the past decade, the C cycle of terrestrial and oceanic ecosystems has been coupled to several global climate models and the simulations have shown that the feedback between C cycling and climate may play an important role in the physical climate system (Friedlingstein *et al.*, 2006; Denman *et al.*, 2007; Meehl *et al.*, 2007). The models generally show a positive feedback between climate and C cycling but with large variations in the magnitude of the resulting atmospheric CO_2 increase (Friedlingstein *et al.*, 2006). Several processes and components that are critical to a more realistic assessment, such as nitrogen cycling and northern peatlands (Frolking *et al.*, in press) have not been included in the present-day coupled terrestrial C climate models. Therefore, inclusion of these processes may influence the overall climate projections (Denman *et al.*, 2007; Thornton *et al.*, 2007; Sokolov *et al.*, 2008). Recent work has shown that the inclusion of the nitrogen cycle could have a very high leverage on the size of the positive feedback (Thornton *et al.*, 2007; Sokolov *et al.*, 2008).

Wetlands cover about 6% of land area of the globe (Matthews and Fung, 1987; Lehner and Doll, 2004), with an area of $5.26\text{-}8.56 \times 10^6$ km^2. About half of wetlands are located between 50-70°N, where > 95% of wetlands are peatlands (Roulet, 2000). The majority of peatland ecosystems accumulate soil carbon because on average net primary production (NPP) exceeds decomposition. Decomposition of peat is reduced because the diffusion of oxygen is inhibited due to water saturation conditions, resulting in low rates of anoxic decomposition. Also peatland vegetation is resistant to decomposition, particularly mosses (Clymo, 1984; Clymo *et al.*, 1998; Charman, 2002; Rydin and Jeglum, 2006). Although northern peatlands have low rate of annual net primary production (NPP) relative to other ecosystems(Frolking *et al.*, 2002; Roulet *et al.*, 2007), peatlands have been continuous carbon sinks at a rate of 20-30 g C m^{-2} yr^{-1} over the past 10,000 years (Gorham, 1991; Frolking *et al.*, 2006; Frolking and Roulet, 2007; Roulet *et al.*, 2007). This has resulted in an estimated store of ~200-450 G t soil

C (Gorham, 1991; Turunen *et al.*, 2001; Bridgham *et al.*, 2006). This represents ~ 16-33 % of global terrestrial soil carbon (Schlesinger, 1997), equivalent to approximately half the mass of atmospheric carbon (Denman *et al.*, 2007). As a rough calculation (this study), the carbon sink rate for the present time, aggregated over all peatlands, is about 0.33 G t C yr^{-1}, which can contribute ~10% of the indentified sink. Moreover, wetlands emit ~ 80-230 Tg CH_4 per year (1 Tg C=10^{12} g C) (Mikaloff-Fletcher *et al.*, 2004). This contributes about 25% of the global methane emissions to the atmosphere from natural emission sources (IPCC, 2007). In fact northern peatlands represent ~10% of the overall wetland contribution to natural methane emissions. Therefore, a small change in the size of this soil C pool could result in a significant change in the global C cycle (Schindler, 1999). Northern peatlands are considered to play an important role in the global C budget (Limpens *et al.*, 2008).

C fluxes between peatlands and the atmosphere are sensitive to climate change and variability (Roulet *et al.*, 1992b; Moore *et al.*, 1998; Chimner and Welker, 2005; Bridgham *et al.*, 2008; Ise *et al.*, 2008) because hydrology and hence their biogeochemistry are intimately coupled to climate (Belyea and Malmer, 2004; Yurova *et al.*, 2007; Ise *et al.*, 2008). Furthermore, northern peatlands are located where future climate is projected to undergo a more severe change (IPCC, 2007). There is unanimous agreement that climate change will be greater on land than on the oceans and whatever emission scenarios are used the global average temperature at high latitudes will increase between +1.8 ℃ and

+4.0 ℃ by 2100 (IPCC, 2007). Precipitation is projected to increase at high latitude as well. Together, both the warming temperature and increasing precipitation could lead to changes in peatland hydrology, which is the dominant controller for peatland maintenance and biogeochemical functions (Charman, 2002; Rydin and Jeglum, 2006). Therefore, the fate of the large store of soil C in northern peatlands in future climate is of concern (Belyea and Clymo, 2001; Belyea and Malmer, 2004; Bridgham *et al.*, 2008; Limpens *et al.*, 2008). Moreover, there is of great concern over whether or not northern peatlands will continue to function as C sinks under the altered climate conditions.

The annual C balance of northern peatlands is composed of several important vertical and horizontal C fluxes (Roulet *et al.*, 2007; Nilsson *et al.*, 2008). The vertical C components, especially CO_2-C, are the primary C flux components between peatlands and the atmosphere (Roulet *et al.*, 2007; Sagerfors, 2007; Nilsson *et al.*, 2008; Sagerfors *et al.*, 2008). Furthermore, CO_2 is the primary contributor to global radiative forcing (1.49 to 1.83 W m^{-2} with an average of 1.66 W m^{-2}) (IPCC, 2007). My study, therefore, will only focus on the vertical CO_2 fluxes between northern peatlands and the atmosphere.

To examine the interactive feedbacks between climate change and C cycling in northern peatlands, we developed a process-based C model, called McGill Wetland Model (MWM), that has the same general structure as Canadian Terrestrial Ecosystem Model (CTEM) (Arora, 2003) and peatland carbon simulator (PCARS) (Frolking *et al.*, 2002), but with different functions for photosynthesis and respiration. The MWM simulates the inputs and outputs of CO_2 and CH_4 as a function of surface and soil climate of a peatland (St-Hilaire *et al.*, 2008). At this stage, however, the MWM only focuses on the CO_2 exchange between peatlands and the atmosphere. The MWM was designed to couple to the newer wetland version of Canadian Land Surface Scheme (CLASS3W) for the inputs of the required surface and soil climates. The MWM was initially developed and successfully evaluated for an ombrotrophic bog (St-Hilaire *et al.*, 2008), which is representative of a significant fraction of northern peatlands.

1.1 General structure of the thesis

This PhD thesis has a total of 7 chapters. The research-based manuscripts include Chapter 3 to Chapter 6, comprising 4 manuscripts.

Northern peatlands are characterized by their hydrology and vegetation composition (Bridgham *et al.*, 1996; Charman, 2002; Rydin and Jeglum, 2006). Northern peatlands are generally subdivided as bogs and fens (Bridgham *et al.*, 1995b; Bridgham *et al.*, 1996; Bridgham *et al.*, 1998). Bogs receive water and nutrients solely from precipitation, whereas fens also receive water and possibly nutrients from surface runoff and surrounding groundwater. The difference in water supply and nutrient inputs between bogs and fens results in differences in soil chemistry, hydrology, nutrient availability, and vegetation structures (Bridgham *et al.*, 1995b; Bridgham *et al.*, 1996; Bridgham *et al.*, 1998; Charman, 2002; Bridgham and Richardson, 2003; Rydin and Jeglum, 2006). These biophysical and biochemical differences lead to the potential differences in greenhouse gas fluxes and biogeochemical processes between bogs and fens. In Chapter 2, I review the relevant general literature on peatlands, carbon cycling and climate change, and specifically the simulation of C cycling in peatlands. Additionally, each manuscript has a more detailed literature review of the relevant literature within the introduction.

It was assumed that the MWM, since it was developed initially for bogs, could not be directly applied to a minerotrophic poor fen without modification. As a result, in Chapter 3, my overall objective was to evaluate, and modify, the original bog version of the MWM (St-Hilaire *et al.*, 2008), if necessary, to simulate the C cycling of northern minerotrophic wetlands, *i.e.* poor fen. I adapted and evaluated MWM to represent the biogeochemical processes in a minerogenic poor fen called Degero Stormyr in Northern Sweden (Sagerfors, 2007; Sagerfors *et al.*, 2008).

Constructing a model for peatland ecosystems, especially for peatland bogs presents a number of unique challenges, one of which is how to deal with the spatial variability that occurs at small scales, *i.e*. 0.5-2.0 m (Belyea and Clymo, 2001; Belyea and Malmer, 2004; Baird *et al.*, in press). The surface of bogs often comprises microtopography, *i.e.* hummocks and hollows, where hydrology and vegetation structures can vary considerably (Malmer and Wallen, 1999; Roy *et al.*, 1999; Weltzin *et al.*, 2001; McMullen *et al.*, 2004; Bubier *et al.*, 2006; Rydin and Jeglum, 2006). In Chapter 4, I attempted to answer the question: "Does the microtopography need to be treated explicitly or can the small scale variability be treated implicitly by a weighted lump of parameters and environmental variables for an ecosystem scale C simulation?”.

To simulate the present C cycling in northern peatlands, all of the required model inputs are obtained from the direct observation at a specific peatland. In addition, we need to simulate the soil and surface climate for examining the fate of the soil C under future changed climate. Therefore, in Chapter 5, we coupled a land surface climate model, CLASS3W with the MWM (referred as CLASS3W-MWM) and evaluated CLASS3W-MWM for Mer Bleue, an ombrotrophic bog in Eastern Canada, and Degero Stormyr, a minerotrophic poor fen in Northern Sweden, where continuous measurements of C, water and energy exchange between peatlands and the atmosphere have been conducted using an eddy-covariance tower (Roulet *et al.*, 2007; Sagerfors *et al.*, 2008).

Finally, the successfully evaluated CLASS3W-MWM was used to examine the sensitivity of the C cycling in northern peatlands in response to the future changing climate. In Chapter 6, we report the C cycling under the future climate up to 2100 for Mer Bleue and Degero Stormyr where the future climate up to 2100 was simulated by the CCCma CGCM3.0 (www.cccma.ec.gc.ca) based on 4 different IPCC climate scenarios, *i.e.* A1B, A2, B1 and Commit.

Chapter 2 Literature review

2.1 Wetlands definition and classification

Wetlands are among the most important ecosystems on the earth (Mitsch and Gosselink, 2000). They are defined as "lowlands, transition zone between terrestrial uplands ecosystem and riparian ecosystems, covered with shallow and sometimes temporary or intermittent waters". Canadian wetlands scientists, based on their research focus mainly on northern inland wetlands, defined wetlands as "land having the water table at, near, or above the land surface or which is saturated for a long enough period to promote wetland or aquatic processes as indicated by hydric soils, hydrophytic vegetation and various biological activities which are adapted to the wet environment." (National Wetlands Working Group, 1988). Another commonly adapted definition is "wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water" (Cowardin *et al.*, 1979). All these wetland definitions reflect the same characteristics: (1) the presence of water at or near the land surface; (2) unique soil conditions with low oxygen content and frequent saturation condition; and (3) specialized biota communities which are adapted to the wet conditions and flooding conditions (Roulet *et al.*, 1997; Mitsch and Gosselink, 2000; Charman, 2002).

Wetlands are distributed everywhere on Earth as long as the local conditions meet the requirements for wetland development (Mitsch and Gosselink, 2000). However, wetlands contain different functional characteristics, such as soil composition, vegetation cover and hydrological conditions (Bridgham *et al.*, 1996; Charman, 2002). This leads to different subtypes of wetlands. From the biogeochemical perspective, wetlands are generally classified as organic wetlands (peatlands), which are the most widespread wetlands at high latitudes in the northern hemisphere, though there are significant peatlands in the tropical region also, and mineral wetlands (Bridgham *et al.*, 1996; Charman, 2002). Combining biota characteristics, hydrological conditions, and morphology, wetlands are classified as bog, fen, swamp, marsh and shallow water body (Mitsch and Gosselink, 2000; Charman, 2002).

More than 90% of wetlands north of 45 °N are peatlands (Roulet *et al.*, 1997; Roulet, 2000). Peatlands are commonly distributed in the boreal region of the northern hemisphere. In Canada, peatlands cover approximately 11% of the country's land area (National Wetlands Working Group, 1988; Roulet *et al.*, 1997; Roulet, 2000). Based on the Canadian classification system, the term peatland is used to describe a subtype of wetlands with a depth of more than 40 cm organic matter in soil (National Wetlands Working Group, 1988; Roulet *et al.*, 1997; Roulet, 2000). Peatlands are formed because plant production exceeds decomposition. The low decomposition is caused by anaerobic conditions due to the low oxygen content owing to the lack of diffusion in water. Some peatland plants are resistant to decomposition, particularly mosses in peatlands (Clymo, 1984; Clymo *et al.*, 1998; Moore and Basiliko, 2006). Based on hydrologic regimes, nutrients and vegetation structure peatlands can be subclassified as bogs or fens (Bridgham *et al.*, 1996; Charman, 2002; Rydin and Jeglum, 2006). Bogs are characterized by water and nutrient inputs from precipitation only. This results in bogs being acidic and nutrient-poor environment. Bogs are mainly covered by mosses and shrubs, but sparse tree may also be present. Fens are fed by precipitation and surface runoff and/or groundwater. This results in more nutrients in fens. Fens are mainly covered by mosses and sedges, but they can also be covered by trees. In this thesis, I will use bogs and fens as the primary classification of northern peatlands.

2.2 Initialization and development of northern peatlands

Peatland development is controlled by both autogenic processes and allogenic, especially climate (Charman, 2002). From a local perspective, the mechanistic controls of peat accumulation are internal. The initialization of peat accumulation and large-scale peatland development and expansion are determined by both topography and climatic conditions (Almquist-Jacobson and Foster, 1995; Halsey *et al.*, 1997; Halsey *et al.*, 1998; Levin, 1998). In addition, the internal shift from fens to bogs at a broader scale is driven by climatic change by altering the hydrologic regime (Zoltai and Vitt, 1990; Yu *et al.*, 2000; Yu *et al.*, 2003; Belyea and Malmer, 2004). Comparatively, topographic conditions in a region are more stable than climatic conditions. Therefore, in a given region, the areal extent of peatlands and their distribution is topographically controlled. But the local expansion or shrinkage is largely climatically controlled.

The fundamental question in general is how wetlands form in the natural world. Hydrology is essential to initiate the development of wetlands (Halsey *et al.*, 1998; Mitsch and Gosselink, 2000; Charman, 2002) and to their maintenance of ecological and biogeochemical functions (Roulet and Woo, 1986; Roulet, 1990; Roulet *et al.*, 1991; Roulet *et al.*, 1997; Roulet and Moore, 2006). There are two basic water balance schemes of wetlands: one is wetlands that receive water only from precipitation (P), which is partitioned between evapotranpiration (E) and outflow (Q), *i.e.* $P \geq E+Q$; the other is wetlands that receive extra water to offset the water loss by evapotranpiration (E) and outflow (Q), *i.e.* $P<E+Q$. As for the former case, because water only comes from precipitation, soil moisture is changing over season due to climatic variability and change, and is undergoing drying and wetting periods. These can be defined as dry wetlands, corresponding to bogs in natural ecosystems. As for the latter case, the maintenance and development of wetlands require water not only from precipitation, but also from surface runon (Is) and groundwater inputs (Ig), *i.e.* $P+Is+Ig>E+Q$. Therefore, the lateral flow will influence the wetlands' maintenance and function. They can be defined as wet wetlands, corresponding to fens in natural ecosystems.

Peatland hydrology and biogeochemistry is intimately coupled to climate, and therefore, can significantly influence the changes in atmospheric CO_2 and CH_4 concentrations if climate were to change (Kaplan, 2002; Gedney and Cox, 2003; Bridgham *et al.*, 2008; Ise *et al.*, 2008). The environmental controls of greenhouse gas emissions (CO_2 and CH_4) from natural peatlands are soil temperature, which affects the soil microbial activities (Bridgham and Richardson, 1992; Bridgham *et al.*, 1995b; Granberg *et al.*, 1997; Weltzin *et al.*, 2000; Weltzin *et al.*, 2003; Chimner and Welker, 2005); water table depth, which determines the depth of oxic and anoxic zones (Roulet *et al.*, 1992a; Roulet *et al.*, 1992b; Moore and Dalva, 1993; Moore and Roulet, 1993; Blodau, 2002; Tuittila *et al.*, 2004)and the quantity and quality of decomposable substrates (Granberg *et al.*, 1997; Walter and Heimann, 2000; Walter *et al.*, 2001). However, the sensitivity of greenhouse emissions from natural wetlands/peatlands to environmental controls, including temperature, precipitation (through the adjustment of the water table depth), and vegetation cover (through the alteration of the quantity and quality of decomposable substrate) are not well understood (Moore *et al.*, 1998; Blodau, 2002).

2.3 Carbon cycling in northern peatlands

The carbon balance of northern peatlands is composed of several vertical and horizontal carbon fluxes (Roulet *et al.*, 2007; Limpens *et al.*, 2008; Nilsson *et al.*, 2008; Sagerfors *et al.*, 2008). The vertical carbon fluxes include the gross uptakes of CO_2 directly through vegetation photosynthesis, the gross losses of CO_2 through vegetation and soil respiration and the integrated fluxes of CH_4 (including the net CH_4 production and net CH_4 assumption). The horizontal carbon fluxes are the lateral inputs and outputs of carbon as dissolved organic and inorganic carbon (DOC/DIC). However, the vertical carbon components, especially CO_2-C, are the primary carbon flux components between peatlands and the atmosphere (Roulet *et al.*, 2007; Sagerfors, 2007; Nilsson *et al.*, 2008;

Sagerfors *et al.*, 2008). Therefore, measurements and simulation of the vertical components of CO_2 fluxes between peatlands and the atmosphere are of great interest to the peatland ecologists and are of critical importance to resolving the carbon dynamics of peatland ecosystem.

While it is generally believed that peatlands remain long-term C sinks (Gorham, 1991), there are very few C balances based on measurements of most of the components of the C balance (Roulet *et al.*, 2007; Nilsson *et al.*, 2008). For example, Nilsson *et al.* (2008) examined all the components of C fluxes in 2004 and 2005 for a minerotrophic mire and found that this mire had a net C sink of 27 and 20 g C $m^{-2}yr^{-1}$ in 2004 and 2005 respectively. Roulet *et al.* (2007) constructed a complete annual C balance for an ombrotrophic bog and derived a 6-year mean C balance of 21.5 g C m^{-2} yr^{-1}, representing a C sink, but with a large annual variability. Though a large variation in annual C fluxes for one peatland site exist, Humphreys *et al.* (2006) examined midsummer C and water fluxes for 7 distinct Canadian peatlands and found a similar net C sink of 1.5 ± 0.2 g C $m^{-2}d^{-1}$ in spite of large differences in water table depth, water chemistry and plant communities. It may be deduced that the large differences in C fluxes among peatland sites are more due to the differences in broad geographic location and physical setting, rather than internal factors such as hydrology, community structure and biogeochemistry (Limpens *et al.*, 2008).

Peatland hydrology and biogeochemistry are intimately coupled to climate (Charman, 2002; Gedney and Cox, 2003; Holden, 2005; Bridgham *et al.*, 2008;

Ise *et al.*, 2008), and therefore, could influence atmospheric CO_2 and CH_4 concentrations if climate were to change. All of the carbon flux components, including the horizontal and vertical components, are more or less determined by soil moisture and air/soil temperature, which is dynamically influenced by soil climate and water table depth (Syed *et al.*, 2006). It has to be acknowledged that vegetation is critically important in C cycling in northern peatlands because C is absorbed by vegetation through photosynthesis and lost through vegetation respiration. Moreover, vegetation can also influence the biogeochemical processes in peat soil, through provision of fresh litter or organic matter substrate and links with hydrology through evapotranspiration process (Chapin III *et al.*, 2002). For example, soil climate and water table depth together determine the slow decomposition rate of organic matter in peat soil. The photosynthesis rate of peatland vegetation, such as mosses and vascular plants, is constrained under both flooded and drier than normal situation (Williams and Flanagan, 1998; Bubier *et al.*, 2003b). Both methane production and methane fluxes are mainly determined by water table depth and vegetation communities (Roulet *et al.*, 1992b; Bubier *et al.*, 1993; Moore and Dalva, 1993; Moore and Roulet, 1993). DOC fluxes are related to soil moisture as well (Fraser *et al.*, 2001; Roulet *et al.*, 2007). Therefore, carbon fluxes between peatlands and the atmosphere should be sensitive to climate change and variability. This raises a concern over whether or not northern peatlands can continue to function as C sinks under the projected climate change: northern peatland regions are projected to experience warmer and possibily drier climate in the near future (IPCC, 2007). Moreover, the high latitude regions of the northern hemisphere contains discontinuous permafrost where climate induced permafrost degradation could result in a shift in peatland hydrology (Chapin III *et al.*, 2000; McGuire *et al.*, 2006; McGuire *et al.*, 2008).

2.4 Simulation of biogeochemical processes in northern peatlands

Peatlands are special natural ecosystems characterized by a waterlogged hydrology, a large store of organic C, a large anaerobic zone, and nonvascular plant dominance (Yu, 2006; Limpens *et al.*, 2008). Therefore, to model the carbon flux dynamics for peatland ecosystem, two special issues must be addressed: 1) unique peat soil decomposition and 2) a unique combination of vegetation communities in northern peatlands (Frolking *et al.*, 2001; Frolking *et al.*, 2002; Yu, 2006; St-Hilaire *et al.*, 2008; Frolking *et al.*, in press). Peat soil is subdivided into two layers, including i) a thick anoxic layer below long-term average water table depth, called the catotelm, and ii) a thin and surface oxic layer above long-term average water table depth, called the acrotelm (Ingram, 1978; Vitt, 2006). The low decomposition rate of peatlands is mainly caused by the slow carbon turnover rate in the underground peat soil (Blodau, 2002; Moore and Basiliko, 2006; Blodau *et al.*, 2007), of which most of the peat soil is subject to anoxic saturated condition. This inhibits both the diffusion of oxygen and the activities of microorganism in the anoxic peat soil. Therefore, hydrology is critical to the maintenance of peatland biogeochemical function.

To simulate peatland hydrology linked to climate, a wetland version of CLASS (Canadian Land Surface Scheme) was developed to include and parameterize the organic soil for simulating the soil climate and hydrology, including water table depth (Letts *et al.*, 2000; Ouyang *et al.*, in press), for bogs and fens. Once water table depth is provided, a special scheme is needed to simulate the inhibited rate of peat soil decomposition due to the saturated anoxic condition (St-Hilaire *et al.*, 2008). In addition, a unique combination of vegetation communities, including sedges, herbs, deciduous and evergreen shrubs, mosses and trees, needs to be considered to fully capture the carbon cycling process in northern peatlands (St-Hilaire *et al.*, 2008). Most of the terrestrial ecosystem models lack the attributes of plant functional types that represent the biogeochemical processes of ericaceous shrubs and mosses.

Simulation of biogeochemical processes in northern peatlands needs to characterize the photosynthesis of vegetation, respiration of vegetation and soil, methane production and consumption, and runoff of organic and inorganic C (Frolking *et al.*, 2002; Yu, 2006; Yurova *et al.*, 2007; Limpens *et al.*, 2008; St-Hilaire *et al.*, 2008). However, the focus of this thesis is on the vertical fluxes of CO_2. C is taken up by peatlands through the photosynthesis of vegetation. This process can be represented by either a Farquhar biochemical function coupled with a canopy-level stomatal conductance (Farquhar *et al.*, 1980; Farquhar and von Caemmerer, 1982; St-Hilaire *et al.*, 2008) or a light use efficiency approach (Frolking *et al.*, 2002). The photosynthesis should be simulated for all the plant functional types in northern peatlands, *i.e.* mosses, sedges, shrubs and trees (if there are trees). Then the photosynthetic C is allocated to vegetation parts, *e.g.* leaves, stems and roots. C is lost to the atmosphere through vegetation respiration, *i.e.* autotrophic respiration that is composed of maintenance and growth respiration, and heterotrophic respiration that is composed of decomposition of fresh litter and soil respiration (Frolking *et al.*, 2002; St-Hilaire *et al.*, 2008). Growth respiration is solely a function of vegetation gross photosynthesis while maintenance respiration is a function of both air temperature and soil moisture. The decomposition of fresh litter is determined by soil temperature and moisture. Soil respiration is composed of aerobic decomposition and anaerobic decomposition where the soil decomposition rates are significantly different from each other (Clymo *et al.*, 1998; Belyea and Clymo, 2001; Frolking *et al.*, 2001; Frolking *et al.*, 2002; St-Hilaire *et al.*, 2008). The decomposition rate of organic matter in the anoxic zone, *i.e.* catotelm, is about one thousand times slower than that in the oxic zone, *i.e.* acrotelm (Clymo *et al.*, 1998; Belyea and Clymo, 2001). Moreover, all of the biogeochemical processes, including photosynthesis and respiration, have a strong and coupled interaction and feedbacks among vegetation composition, peat temperature and soil moisture (or water table depth) (Belyea and Clymo, 2001; Belyea and Malmer, 2004; Belyea and Baird, 2006).

Though there are a couple of models developed to simulate the C balances in northern peatlands based on either the site-specific field measurements or the fundamental biogeochemical processes (Frolking *et al.*, 2001; Frolking *et al.*, 2002; Zhang *et al.*, 2002; Yurova *et al.*, 2007; St-Hilaire *et al.*, 2008; Wania *et al.*, in press), northern peatlands have been consistently ignored in global C assessments (Limpens *et al.*, 2008) . At present, the contemporary C cycling in northern peatlands has been identified as a large gap in the assessment of the global C budgets and the feedbacks with the climate change (Limpens *et al.*, 2008; Huntingford *et al.*, 2009). Both empirical regression models and process-based models have been developed to simulate/assess the C cycling in northern peatlands at local sale or regional/national scale. A statistical regression model can be developed based on the relationship between seasonal and/or annual C fluxes and the observed biophysical parameters, such as peat temperature, water table depth, air temperature and solar radiation (Roulet *et al.*, 1992b; Moore and Roulet, 1993; Granberg *et al.*, 1997). Normally, the statistical regression model can only be valid within the limits of its biophysical drivers. Thus, it is questionable to extrapolate this kind of relationship to assess the C cycling under the future changed climate, because it is likely that the future changed climate can be beyond the present climate states on which the regression model was developed. Therefore, a process-based model should be used to examine the sensitivity of C cycling and the organic C stored in northern peatlands to the future changed climate. Process-based models can also be developed by simulating the photosynthesis, vegetation respiration and soil respiration respectively as a function of the commonly-observed soil and surface climate, such as solar radiation, air temperature, peat temperature, soil moisture and water table depth (Frolking *et al.*, 2002; Zhang *et al.*, 2002; Yurova *et al.*, 2007; St-Hilaire *et al.*, 2008; Wania *et al.*, in press). For example, Frolking *et al.* (2002) developed the peatland carbon simulator (PCARS) to simulate photosynthesis and respiration of vascular and non-vascular vegetation based on an approach of light use efficiency, and soil decomposition by linking to a model that simulates long-term peat accumulation (Frolking *et al.*, 2001), an essential component to simulate anaerobic decomposition. Zhang *et al.* (2002) modified the upland ecosystem model, DNDC (Denitrification and Decomposition), and developed a wetland version of this model, wetland-DNDC by incorporating new functions to characterize the peatland hydrology, soil properties and vegetation communities. Yurova *et al.* (2007) modified LPJ-GUESS to simulate the daily net ecosystem exchange (NEE) by adding new functions to describe the photosynthesis of *Sphagnum* moss and decomposition of peat. Wania *et al.* (in press) incorporated peatlands into a global dynamic vegetation model (LPJ) and simulated the net ecosystem production (NEP), heterotrophic respiration (HR) and soil carbon contents by adding 2 new peatland-specific plant function types, an inundation stress mechanism and deceleration of decomposition under inundation.

2.5 Evaluation criteria

Objective criteria are needed to evaluate model performance. A useful statistical index for evaluating how well the modelled carbon fluxes fit measured fluxes is the total root mean square errors (RMSE), that describes the systematic RMSE(RMSEs) and unsystematic RMSE (RMSEu) where $RMSE^2=RMSEs^2+RMSEu^2$, and the Willmott degree of agreement (d*). These statistical index were developed and outlined by Willmott (1982, 1985) and have been commonly used in meteorological and climate research for modelling test and evaluation (for example,Comer *et al.* (2000), Lafleur *et al.* (2000), Letts *et al.* (2000)). They are calculated as follows:

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (P_i - O_i)^2 \right]^{\frac{1}{2}} \qquad (2.1)$$

$$RMSEs = \left[\frac{1}{n} \sum_{i=1}^{n} (P_i^{*} - O_i)^2 \right]^{\frac{1}{2}} \qquad (2.2)$$

$$RMSEu = \left[\frac{1}{n} \sum_{i=1}^{n} (P_i^{*} - P_i)^2 \right]^{\frac{1}{2}} \qquad (2.3)$$

$$d^{*} = 1 - \left[n(RMSE)^2 \frac{1}{\sum_{i=1}^{n} (\left|P_i - \overline{O}\right|) + \left|O_i - \overline{O}\right|)^2} \right] \qquad (2.4)$$

where n is the number of observations, *Pi* and *Oi* are the *i*th values of the predicted (modelled) and measured quantities respectively, *Pi*=a+bOi* where a and b are parameters according to the least square regression between O and P, $\overline{O}$ is the average value for n measured quantities (O).

The Willmott degree of agreement presents the performance of a model very well because it is calculated based on the direct comparison between the modelled outputs and the observed ones (Willmott, 1982, 1985). So it not only defines the relationship between the modelled outputs and observed ones, but also describes the discrepancy between them. This non-dimensional Willmott degree of agreement (d*) ranges between 0 and 1, where 0 means that there is no agreement between modelled outputs and observation and 1 means that there is fully perfect agreement between modelled outputs and observation. A “good” model can be indicated by a high value of d*. Logically, a “good” model should have a low RMSE with correspondingly low RMSEs and RMSEu. RMSEu, representing the unsystematic errors, is a measure of model parameterization that can usually be corrected by tuning-up of model parameters. RMSEs, representing the systematic errors, is a measure of a model's potential accuracy in its current formulation. Therefore, a "good" model should have a higher RMSEu than RMSEs, because a higher value of RMSEs signifies that there is no clear relationship between modelled output and observation. This means that only model reformulation, rather than parameter tuning-up, should be conducted to improve the model's performance (Willmott, 1985; Comer *et al.*, 2000).

2.6 Scientific questions and objectives

For peatlands, five big questions are important: (1) What is the present role of northern peatlands in the global C budget? (2) What are the spatial and temporal characteristics of C cycling in northern peatlands? (3) How will the C cycling in northern peatlands respond to natural disturbance, such as fire, and human disturbance, such as peatland drainage, peat extraction and land cover change? (4) How will the C cycling in northern peatlands respond to the future projected climate change? And (5) what is the future role of northern peatlands in global C budget under a changing climate? In this thesis, the McGill Wetland Model (MWM) (in chapter 3 and 5) is developed and used to shed some light on the fourth and fifth question.

The specific objectives of my thesis are: (1) to parameterize and modify, if necessary, the MWM for simulating the C cycling for a northern fen peatland; (2) to examine the impact of microtopography on the simulation of ecosystem-level C cycling for a bog peatland; (3) to couple MWM with a land surface climate model (*i.e.* CLASS3W) for assessing the C cycling under the future changed climate in northern peatlands (referred as CLASS3W-MWM); (4) to study the C cycling in northern peatlands under the future climate up to 2100 simulated by CCCma GCM using CLASS3W-MWM.

Chapter 3 Six years simulation of carbon fluxes for a minerotrophic mire (poor fen) in Northern Sweden using the McGill Wetland Model (MWM)

This chapter is based on a manuscript in preparation entitled:

Wu, Jianghua and others, Six years simulation of carbon fluxes for a minerotrophic mire (poor fen) in Northern Sweden using the McGill Wetland Model (MWM).

3.1 Introduction

Wetlands cover about 6% of the global land area (Matthews and Fung, 1987; Lehner and Doll, 2004). About half of wetlands are located between 50-70°N, of which > 95% are peatlands (Roulet, 2000). Peatland ecosystem accumulates carbon, because, on average, net primary production (NPP) exceeds decomposition. Peatlands store up to 450 G t soil C (1 G t C=10^{15} g C) (Gorham, 1991; Turunen *et al.*, 2002) representing ~ 20% of global terrestrial soil carbon (Schlesinger, 1997). Northern wetlands represent ~10% of the wetland contribution to natural methane emission (Mikaloff-Fletcher, *et al.* 2004). Carbon fluxes between peatlands and the atmosphere are sensitive to climate variability and change (Moore *et al.*, 1998; Roulet *et al.*, 2007; Ise *et al.*, 2008; Sagerfors *et al.*, 2008) , through the links between hydrology and peatland biogeochemistry (Charman, 2002; Gedney *et al.*, 2004; Yurova *et al.*, 2007; Ise *et al.*, 2008). Northern peatlands are located where future climate is projected to undergo a significant change (IPCC, 2007). The fate of this large store of carbon in peatlands in future climate is, therefore, of concern (Belyea and Malmer, 2004; Roulet *et al.*, 2007). In this study we adapt the McGill Wetland Model (MWM) (St-Hilaire *et al.*, 2008), originally developed to simulate carbon exchange in bogs, for use in mineral poor fens, an equally common northern peatland type as bogs.

Over the past decade, the carbon cycle of terrestrial and oceanic ecosystems has been coupled to several global climate models and simulations show that the feedback between carbon cycling and climate can play an important role in the physical climate system (Friedlingstein *et al.*, 2006; Denman *et al.*, 2007). The models all show a positive feedback between climate and carbon cycling but with large variations in the magnitude of the resulting CO_2 increase in the atmosphere (Friedlingstein *et al.*, 2006). However, northern peatlands have not been included in these models. The MWM, based on the general structure of the Canadian Terrestrial Ecosystem Model (CTEM) (Arora, 2003) was developed to simulate the inputs and outputs of CO_2 as a function of surface and soil climate of a peatland (St-Hilaire *et al.*, 2008). The MWM was successfully evaluated for an ombrotrophic bog (St-Hilaire *et al.*, 2008), but its suitability for other major peatland types has not been assessed. Minerotrophic poor fen represents a second extensive northern peatland type (Charman, 2002). We adapted the MWM for the biogeochemical processes in minerogenic poor fens and evaluated the modified MWM for Degero Stormyr, in northern Sweden, where the eddy-covariance measurements of the exchange of energy, water and carbon between peatlands and the atmosphere have been continuously conducted for 6 years, 2001-2006 (Sagerfors *et al.*, 2008). We did not expect the MWM to work well for minerotrophic poor fens without modification because fens have a different hydrology and vegetation structure than ombrotrophic bogs (Sagerfors *et al.*, 2008; St-Hilaire *et al.*, 2008).

The following modifications were implemented in the MWM for fens. Firstly, a new scheme of moss water dynamics was introduced. Secondly, sedge root dynamics were introduced to soften the boundary between the oxic and anoxic zones. Lastly, gross primary production was constrained by a function including water table depth (WTD) to take into account the flooded and drier conditions. With the inclusion of these modifications, we examined how well the MWM simulated the daily, seasonal and inter-annual variability in direction and magnitude of carbon exchange between a fen peatland and the atmosphere. We conclude with a sensitivity analysis of fen carbon exchanges to variations in climatic inputs and some key internal parameters.

3.2 Model description

The MWM solves carbon storage in 3 plant pools - leaves, stems and roots, and 1 soil pool. There is a fifth C pool for storing each year's fresh litter that decomposes faster than the soil pool. The current input variables for the stand-alone version of the MWM are observed net radiation, photosynthetic photon flux density, precipitation (rain or snow), water table depth (WTD), air and soil temperature, relative humidity, wind speed, atmospheric pressure, and CO_2 concentrations. The current outputs are gross primary production (GPP) and autotrophic respiration (AR) for each plant functional types (PFT), and oxic and anoxic decomposition for the soil profile. The MWM simulates the carbon cycling through two fundamental biogeochemical processes: CO_2 uptake by photosynthesis and CO_2 loss by autotrophic and heterotrophic respiration. The MWM can simulate CH_4 exchange and DOC loss as well, but these functions at present are identical to those of the Peatland Carbon Simulator (PCARS) (Frolking *et al.*, 2002).

In the MWM, there are 4 PFT to represent the vegetation communities in northern peatlands: trees, shrubs, sedges, and mosses. Photosynthesis in vascular plants is simulated by a Farquhar biochemical approach (Farquhar *et al.*, 1980; Farquhar and von Caemmerer, 1982), coupled with canopy-level stomata conductance (Jarvis, 1976; Ball *et al.*, 1987) to solve an optimal PFT-specific GPP (Arora, 2003; St-Hilaire *et al.*, 2008). For mosses, a semi-empirical function of the effect of moss water content on photosynthetic capacity (Tenhunen *et al.*, 1976) and total conductance of CO_2 (Williams and Flanagan, 1998) replaces stomatal conductance. A simple degree day approach is used for the vegetation phenology. The autotrophic respiration is composed of maintenance and growth respiration. Both mosses and vascular plant produce fresh litter. Soil decomposition is the sum of first-year fresh litter and peat decomposition. After decomposition in the litter pool during the year of production the reminder becomes input to the peat profile.

The modifications to the MWM for use in northern fens are now described.

3.2.1 Moss water content dynamics

Moss water content is required to compute the total CO_2 conductance for moss (Williams and Flanagan, 1998). Mosses have two sources of water: intercepted precipitation and capitulum uptake from the peat. The former is surface moss water (Θ_s) represented by a function of both precipitation and the interception capacity of the moss (Θ_{cap}), and the latter is internal moss water (Θ_i)

represented by a function of WTD, Θ_s and moss holding capacity (Θhold). The total moss water content (Θ_t) is then the sum of the two water sources:

$$\frac{d\Theta t}{dt}=\frac{d\Theta s}{dt}+\frac{d\Theta i}{dt} \quad \text{or} \quad \Theta_t = \Theta_s + \Theta_i \qquad (3.1)$$

We simulate the intercepted precipitation when it rains by (St-Hilaire *et al.*, 2008):

$$\Theta s = \text{minimum}\ (\Theta cap,\ \Theta(t)+\frac{\rho_{water}\times hppt}{folmass\_moss}) \qquad (3.2)$$

where all water contents are expressed in g water/g dry moss; ρ_{water} is the density of fresh water (g m^{-3}); hppt is the hourly precipitation rate (m hr^{-1}) and *folmass_moss* is moss foliar biomass (g m^{-2}).

Moss internal water constrains moss photosynthesis (Rydin and Jeglum, 2006). Two processes are involved in the dynamics of moss internal water: capitulum uptake and rehydration from surface moss water (Θ_s). Firstly, moss internal water (Θi) is simulated as an exponential function of WTD, with the maximum internal water determined by moss holding capacity (Θhold) (Hayward and Clymo, 1982):

$$\Theta i = \text{minimum}\ (\Theta hold,\ a\times \exp(b\times WTD^{c})) \quad (3.3)$$

where a, b and c are based on the peatland function type, *e.g.* bog or fen. We have set a=15, b= -30 and c=2.5 to capture the moss water content dynamics for a poor fen ecosystem (Hayward and Clymo, 1982). Secondly, if Θi is smaller than Θhold and $\Theta_s > 0$, moss can rehydrate from moss surface.

Since the stand-alone version of the MWM does not have the drying process, it is approximated by:

$$\Theta s(t) = \Theta s(t-1) \times \exp(-k_d) \qquad (3.4)$$

where k_d is a site-specific parameter for the constant drying rate, which is used to estimate the appropriate evapotranspiration rate (Frolking *et al.*, 2002). In climate simulation, this is replaced by actual evapotranspiration, computed in the land surface scheme (For example, Canadian Land Surface Scheme (CLASS) (Verseghy, 1991; Verseghy *et al.*, 1993)). Moss internal water is not subject to drying until Θs=0. It is assumed that moss internal water is more difficult to lose than moss surface water. So moss internal water is subject to an exponential drying, similar to moss surface water, but at 1/10 of the rate of moss surface water.

3.2.2 The effect of soil water stress on optimal GPP

The photosynthesis of most vegetation can suffer from soil water stress during the period of both flooded and drier than optimal conditions (Knorr, 2000; Cox, 2001; Arora, 2003; Jassal *et al.*, 2008) because photosynthesis responds non-linearly to a combination of multiple environmental variables (Arora, 2003). Several empirical approaches have been applied in terrestrial ecosystem models to modify optimal GPP for these conditions with respect to water availability and one is a soil water stress (Warnant *et al.*, 1994; Foley *et al.*, 1996; Knorr, 2000; Arora, 2003). For our situation we adapt this index as a function of the WTD:

$$G_{stressed}=G_{unstressed}\times f(\Omega)\quad(0\leq f(\Omega)\leq 1)\quad(3.5)$$

where $G_{unstressed}$ is the unstressed GPP rate; $f(\Omega)$ is a soil water stress function; and $G_{stressed}$ is the actual GPP rate with respect to the soil water stress on vegetation photosynthesis activity. For peatlands, $f(\Omega)$ is replaced with a function of WTD, ω:

$$\omega=\begin{cases}\max(0.0001,(\frac{0.1+WTD}{0.2})^{1.5} & WTD\leq 0.1m\\ 1.0 & 0.1m\leq WTD\leq 0.2m\\ \max(0.0001,(\frac{0.55-WTD}{0.35})^{\frac{1.0}{1.5}} & WTD\geq 0.20m\end{cases}\qquad(3.6)$$

3.2.3 Decomposition

Carbon stored in peat soil undergoes both oxic and anoxic decomposition that is to be heterotrophic respiration (HR). The subdivision of the oxic and anoxic zone in the MWM is by an effective water table depth (St-Hilaire *et al.*, 2008), but in fens the live roots of the vascular plants extend into the saturated zone (Moore *et al.*, 2002) where they constitute a sufficiently large active biomass to transport O_2 below the water table. To simulate the dynamics of this extension of the oxic zone a function representing sedge rooting was implemented. Root depth was simulated as a non-linear function of vegetation net primary production (NPP = GPP - AR):

$$root\_depth = 2.5\left(\frac{NPP\_sedge}{5.0}\right)^{1.5} \qquad (3.7)$$

where *NPP_sedge* is the daily sedge NPP (g C $m^{-2}d^{-1}$) and *root_depth* is the daily maximum sedge root depth (m). The bulk of the mass of roots occur well above the maximum root depth (Moore *et al.*, 2002) and these rest roots are not effective O_2 transporters. To partition oxic and anoxic zones with roots modifying the effective water table depth (WTD_{eff}) we use:

$$WTD_{eff} = 0.75 \times root\_depth \quad \text{if } WTD \leq 0.75 \times root\_depth \qquad (3.8.1)$$

$$WTD_{eff} = WTD \quad \text{if } WTD > 0.75 \times root\_depth \qquad (3.8.2)$$

3.3 Site and data sets

3.3.1 Site description

The study was conducted at Degerö Stormyr (64°11’N, 19°33’E) (herein referred as DS), an acid, oligotrophic, minerogenic, mixed mire system covering 6.5 km^2 situated in the Kulbäcksliden Experimental Forest, near Vindeln in the county of Västerbotten, Sweden (Sagerfors, 2007; Sagerfors *et al.*, 2008). The depth of the peat is generally between 3-4 m, but depth up to 8 m was also observed. The deepest peat corresponds to an age of basal ~8000 years old.

The climate of the region is cold temperate humid with a 30-year average annual precipitation and temperature of 523 mm and 1.2 ℃ respectively, and average monthly temperatures in July and January of 14.7 ℃ and -12.4 ℃ (Alexandersson *et al.*, 1991). The length of growing season, defined as the period of daily mean temperature > 5 ℃ (Moren and Perttu, 1994), was ~153 days for the study period of 2001-2006 (Sagerfors *et al.*, 2008). The snow cover normally reaches a depth of 0.6 m and lasts for six months. The mean water table level is 10 to 15 cm below the peatland surface.

The vascular plant community is dominated by *Eriophorum vaginatum* L., *Vaccinium oxycoccos* L., *Andromeda polifolia* L.,*Rubus chamaemorus* L. with both *Carex limosa* L. and *Schezeria palustris* L. occurring more sparsely. *Carex rostrata* L. is found within the margins of this fen, where there is a direct minerogenic water inflow. The surface vegetation in the wet carpets is dominated by *Sphagnum majus* Russ. C. Jens, and the lawns by *S. balticum* Russ. C. Jens. and *S. lindbergii* Schimp, while *S. fuscum* Schimp. Klinggr. and *S. rubellum* Wils. are dominant on the hummocks.

3.3.2 Observation data sets

The CO_2 fluxes in the MWM are simulated as a function of environmental variables, such as soil and surface climate (St-Hilaire *et al.*, 2008). These drivers for the model can either be directly input to the MWM from the field measurements for a specific research site in this case DS, or can be obtained from a land surface model. The MWM was run at an hourly time step. In this study, hourly input data were from the observations at DS. To fully represent the site-specific biogeochemical processes, several site-specific parameters are required (Table 3.1), such as peat depth, foliar biomass and V_{cmax25} (which is the maximum velocity of Rubisco carboxylation at 25 ℃) for mosses and sedges, and root biomass for the sedges. In addition to these site-specific parameters, a complementary data set containing model parameters based on studies reported in the literature serves for all sites within a range of general northern peatlands types (see Table 1 in St-Hilaire *et al*, 2008).

Table 3.1: Parameters and initial values used in MWM simulation for Degero Stormyr (DS) poor fen.

Parameter	Value	Units	Description	Reference/Source
Values for Model Parameters at 25°C				
J_{max}:V_{max}	1.67	-	ratio	(Medlyn *et al.*, 2002)
mosses				
V_{cmax25}	6.5	µmol $m^{-2}s^{-1}$	max carboxylation rate (spring)	M. Nilsson unpublished
	14	µmol $m^{-2}s^{-1}$	max carboxylation rate (summer)	
	7.5	µmol $m^{-2}s^{-1}$	max carboxylation rate (autumn)	
R_{d25}	0.946	µmol $m^{-2}s^{-1}$	dark respiration rate	(Harley *et al.*, 1986)
Sedges				
V_{cmax25}	20	µmol $m^{-2}s^{-1}$	max carboxylation rate	M. Nilsson unpublished
Site specific				
frac	48.7	%	biomass to carbon ratio	T.R. Moore unpublished
B_{moss}	144	g dry biomass m^{-2}	moss capitula biomass	(Moore *et al.*, 2002)
$B_{min\ foliar}$	90	g dry biomass m^{-2}	min sedge foliar biomass	
$B_{max\ foliar}$	180	g dry biomass m^{-2}	max sedge foliar biomass	
B_{stem}	0.003	$m^3\ m^{-2}$	shrub sapwood volume	
PD_0	3	m	initial peat depth	(Sagerfors, 2007)
Others				
θ_{lim}	0.04/0.15	-	residual soil-water content in fibric/hemic peat	(Letts *et al.*, 2000)
θ_p	0.93/0.88	-	soil porosity in fibric/hemic peat	
ψ_{sat}	0.0103/0.0102	m	soil matric potential at saturation in fibric/hemic peat	
b	2.7/4.0	-	soil texture parameter in fibric/hemic peat	
Θ_{maxcap}	15	g H_2O /g dry biomass	maximum holding capacity of moss	(Silvola, 1990)
Θ_{mincap}	5	g H_2O /g dry biomass	minimum interception capacity of moss	(Price *et al.*, 1997)
k_d	1	%	water loss rate in capitulum	(Frolking *et al.*, 1996)
k_o	0.05/0.2	y^{-1}	initial decomposition rate for moss/sedge	T.R. Moore unpublished

We ran the MWM based on the environmental variables that have been continuously measured at DS for 6 years from January 1 2001 to December 31 2006. To evaluate the simulated outputs from the MWM we used the gap-filled eddy-covariance net ecosystem exchange (NEE) for DS (Sagerfors, 2007; Sagerfors *et al.*, 2008). Details on the measurements, gap-filling and data quality procedures can be found in Sagerfors *et al* (2008). We have done the following processes to fill the gaps of the environmental drivers for the evaluation period from Jan.1 2001 to Dec. 31 2006: (1) determined the snowfall to be zero in the growing season, usually from May 1 to October 1; (2) used a linear interpolation and extrapolation to derive the required three-layers of soil temperature from the different layers of measured soil temperature at 10cm, 18cm and 42cm; (3) for WTD, if gaps existed, we used the previous 5 hours moving average to fill the gaps and (4) for the gaps of other environmental drivers, we used the hourly averages in the past or the future at the same time to fill the gaps.

3.4 Evaluation

The primary statistical index used in this study for evaluating how well the modelled carbon fluxes fit to the measured fluxes is the root mean square errors (RMSE), which can be divided into the systematic RMSE (RMSEs) and unsystematic RMSE (RMSEu) ($RMSE^2=RMSEs^2+RMSEu^2$) (St-Hilaire *et al.*, 2008). We also used an index of agreement (d*) developed by Willmott (1982) and Willmott (1985). d* ranges 0-1, where 0 means no agreement between simulated and observed values; while 1 indicates perfect match between them.

3.5 Results and discussions

To evaluate the performance of the MWM for a poor fen, we first assessed how well the original MWM simulated net ecosystem production (NEP) for DS. Then we ran the modified MWM to assess its performance in capturing the annual and seasonal patterns and magnitude of CO_2 exchanges by comparing the modelled outputs with 6 years of continuous NEP measurements at DS. Here we used the terminology net ecosystem exchange (NEE) to represent the net ecosystem production (NEP) (Chapin III *et al.*, 2006), where NEP (= -NEE) is the difference between GPP and total ecosystem respiration (TER). Positive NEP means C uptake by the ecosystem. Following this, we examined the annual and seasonal patterns of NEP. In addition, we discussed with reference to the literature how well the MWM simulates net primary production (NPP) and then look at how NEP relates and is sensitive to some key climate variables – *e.g.* water table depth (WTD) and air temperature (Ta). We also examined the sensitivity of the MWM outputs to changes in several key parameters, such as moss water contents (Θ), water stress index (ω) and sedge root depth (root_depth).

It should be noted that errors and uncertainties can be fairly large in a comparison of simulated NEP and measured NEP over short time periods - *i.e.* hourly and daily, but they reduce dramatically for the longer time scale - *i.e.* annually (Hagen *et al.*, 2006). In the MWM, NEP is derived as the difference between two large numbers, GPP and TER, hence relatively small errors in GPP and TER will propagate into large errors in NEP. Generally, the statistical indices for describing the model's performance are much better if the evaluation criteria is based on the comparison of modelled and measured GPP and/or TER rather than only based on the comparison of modelled NEP with measured NEP (St-Hilaire *et al.*, 2008), but NEE is the direct empirical observation.

3.5.1 NEP simulation for DS with the original MWM

Using the original MWM formulation but with poor-fen specific parameters and sedges included as a PFT at DS resulted in a consistent bias of a too large net uptake during the growing season and a too large loss during the non-growing season, especially during the later part of the growing season and also most pronounced during the drier and wetter years (Fig.3.1 and 3.2), even though the inter-annual and seasonal trends were reproduced fairly well. Overestimation mainly happened in the growing season when WTD was fluctuating. Simulated NEP ranges between 79 and 182 g C m^{-2} yr^{-1} with an average of 152 g C m^{-2} yr^{-1}, while the observed NEP ranges between 17 and 60 g C m^{-2} yr^{-1}. Overestimation for years 2001, 2002 and 2005 is significant during the study period. These 3 years were consistently wetter than normal (Sagerfors, 2007; Sagerfors *et al.*, 2008). Overestimation for year 2006 is also significant, which was a very dry year where WTD reached 40 cm below the surface. The RMSE between the simulated NEP and observed NEP was 0.85 g C m^{-2} d^{-1} and d* was ~0.65 with a r^2 of 0.37. Both d* and r^2 shows that the original MWM cannot capture the characteristics of the CO_2 exchange for DS very well.

3.5.2 NEP simulation with the MWM modified to fen conditions

3.5.2.1 Annual patterns of simulated and measured C exchange fluxes

In general the fen version of the MWM simulates the magnitudes and inter-annual variability of annual NEP very well (Table 3.2, Fig. 3.3). The comparison of simulated annual NEP with the measured annual NEP shows no systematic bias. Among the 6 years, the maximum measured NEP is 60 g C m^{-2} yr^{-1} in 2002, while the maximum simulated NEP is 61 g C m^{-2} yr^{-1}, also in 2002. The minimum measured NEP is 17 g C m^{-2} yr^{-1} in 2006, while the minimum simulated NEP is 15 g C m^{-2} yr^{-1}, also in 2006. There were three years of overestimation with maximum of 3 g C m^{-2} yr^{-1}; while there were also three years of underestimation with maximum of 15 g C m^{-2} yr^{-1}. The relative discrepancy between the modelled and observed annual NEP ranges from -15% to +6% (Table 3.2). The simulated NEP also reproduced a similar year-to-year variation pattern (Fig.3.3). The MWM captures the carbon cycling processes better in the growing season than in the non-growing season. The model overestimates the carbon losses in both the spring and winter time. We could not isolate this to one specific modelling process.

Fig. 3.1: Comparison of measured and simulated daily NEP for 2001-2006 at DS using the original MWM.

Comparison of measured and simulated daily NEP for 2001-2006 at DS using the original MWM, parameterized for a poor fen (Solid dark circles for the tower observed NEP and blank circles for the MWM simulated NEP). Positive NEP means carbon sinks; while negative NEP means carbon sources. In general, the original MWM consistently overestimated daily NEP, both the net uptake during the growing season and the net loss during the non-growing season. The growing season discrepancy was most pronounced during fall.

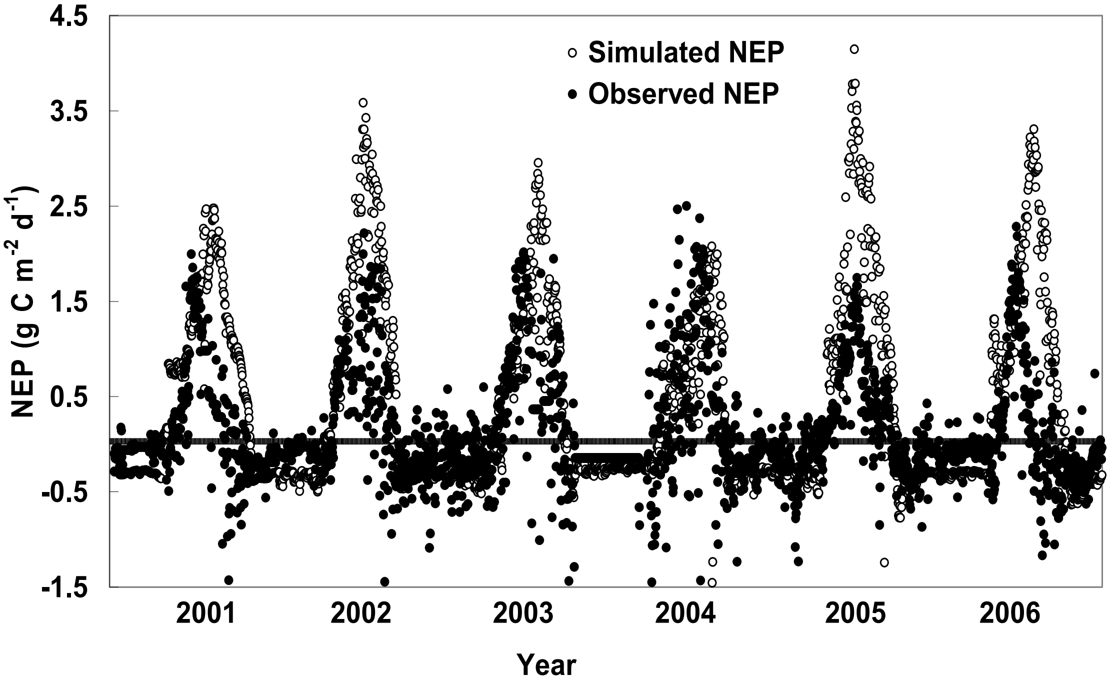


Fig. 3.2: Accumulated annual tower measured and simulated NEP using the original MWM.

Accumulated annual tower measured NEP (Observed NEP) and simulated NEP using the original MWM parameterized for a poor fen for 2001-2006 (Solid dark circles for tower measured NEP (Observed NEP) and blank circles for MWM simulated NEP. Positive NEP indicates carbon sinks; negative NEP means carbon sources. Generally, the original MWM significantly overestimates the annual NEP, especially for wetter and drier years.

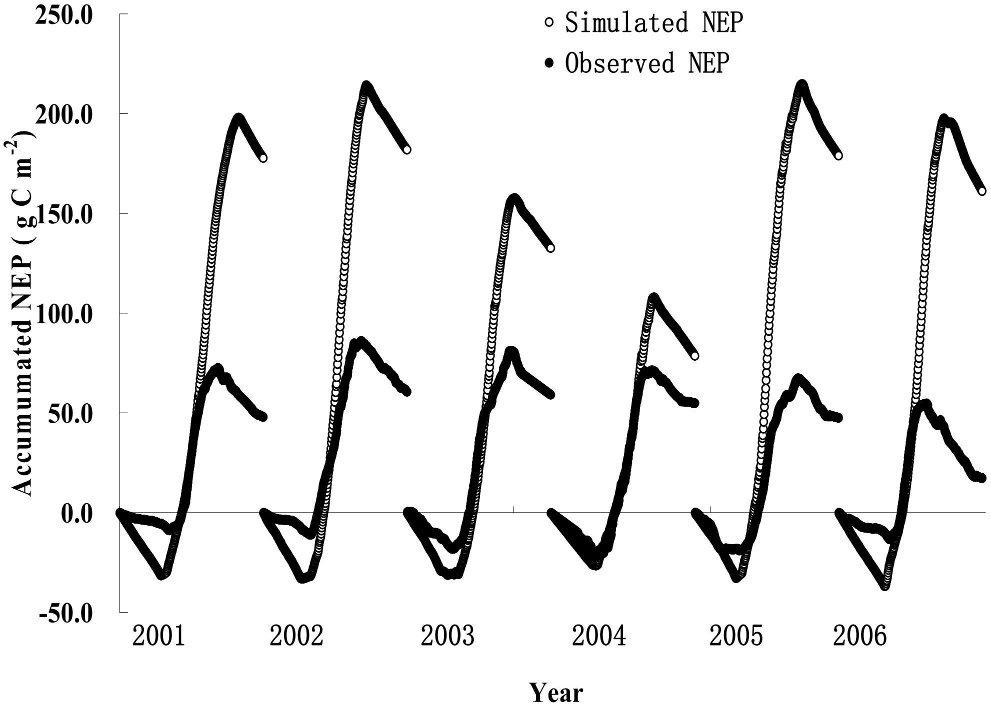


Fig. 3.3: Accumulated annual tower measured and simulated NEP using the modified MWM.

Accumulated annual tower measured NEP (Observed NEP) and simulated NEP using the modified MWM for 2001-2006 (Solid dark circles for tower measured NEP (Observed NEP) and blank circles for MWM simulated NEP). Positive NEP indicates carbon sinks; negative NEP means carbon sources. Note: Different scale for Y axis than that in Fig. 3.2.

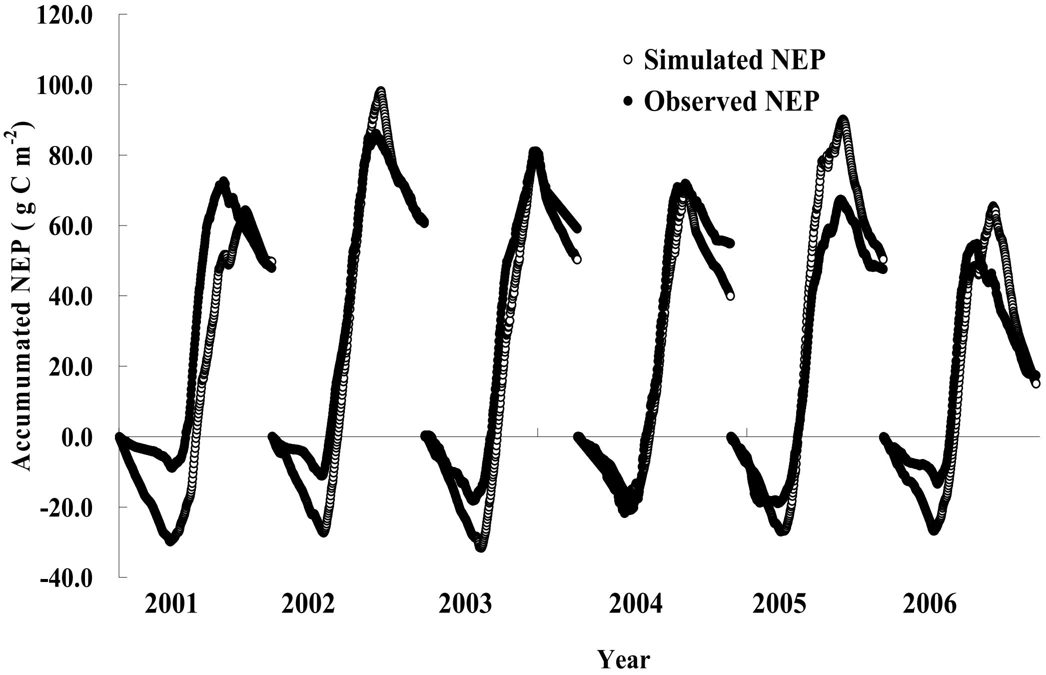


Table 3.2: Tower measured (Tower), Modelled (Model) annual NEP and the difference between them; Modelled annual GPP, NPP and TER, and moss and sedge contribution to them respectively, for 2001-2006 at DS.

Note*: The unit for the carbon fluxes is g C m^{-2} yr^{-1}.

	NEP				**GPP**			**NPP**					**TER**				
Year	Tower*	Model*	Diff.	Dev.	GPP*	Moss	Sedge	NPP*	Moss-NPP*	Sedge-NPP*	Moss	Sedge	TER*	AR	MossAR	SedgeAR	HR
				%		%	%				%	%		%	%	%	%
2001	47.91	49.66	1.75	3.65	393.97	35.40	64.60	113.91	66.65	47.26	58.51	41.49	344.30	81.34	21.15	60.19	18.66
2002	60.60	61.06	0.46	0.77	593.12	31.50	68.50	229.44	79.52	149.93	34.66	65.34	532.06	68.35	20.17	48.18	31.65
2003	59.06	50.29	-8.77	-14.85	455.38	34.98	65.02	161.25	83.48	77.77	51.77	48.23	405.09	72.61	18.71	53.90	27.39
2004	54.86	39.94	-14.92	-27.19	352.72	42.84	57.16	120.61	91.76	28.84	76.08	23.92	312.77	74.21	18.98	55.23	25.79
2005	47.54	50.31	2.77	5.82	477.33	30.57	69.43	158.93	59.50	99.42	37.44	62.56	427.03	74.56	20.23	54.33	25.44
2006	17.27	14.69	-2.58	-14.95	418.58	32.01	67.99	137.86	59.13	78.73	42.89	57.11	403.89	69.50	18.53	50.97	30.50
Ave.	47.87	44.33	-3.55	-7.79	448.52	34.55	65.45	153.67	73.34	80.32	50.23	49.77	404.19	73.43	19.63	53.80	26.57
Std. Dev.	15.95	15.98	6.95	13.17	83.47	4.50	4.50	41.83	13.55	42.34	15.49	15.49	75.92	4.61	1.04	4.07	4.61

The dev. (mean deviation) is calculated by: (Model-Tower)/Tower ×100%

For a minerotrophic poor fen, the MWM simulates moss and sedge GPP separately to obtain ecosystem level total GPP. GPP at DS ranges between 393 and 593 g C m^{-2} yr^{-1} with an average of 448 g C m^{-2} yr^{-1}. The moss GPP ranges between 31% and 42% with an average of 35% of total GPP, while sedges range between 58% and 69% with an average of 65%. Over the 6 years, the annual contribution of both mosses and sedges to total GPP varies by 4.5%. This shows that the variation in simulated annual relative contribution of mosses and sedges to total GPP is minor even though the magnitude of GPP varies from year to year.

TER ranges between 312 and 532 g C m^{-2} yr^{-1} (mean 404±75 g C m^{-2} yr^{-1}), with an AR contributing between 68% and 81% (mean 73%±5%) and HR between 19% and 32% (mean 27%±5%). Moss AR represents 19- 21% (mean 20%±1%) of the overall TER, while sedges represent between 54% and 60% (mean 54%±4%).

NPP shows a different pattern than the GPP and the autotrophic respiration respectively. NPP ranges between 114 and 230 g C m^{-2} yr^{-1} with an annual variability of ±42 g C m^{-2} yr^{-1}. Moss NPP ranges between 59 and 92 g C m^{-2} yr^{-1} (35% to 76% of overall NPP) and sedge NPP ranges between 29 and 150 g C m^{-2} yr^{-1}(24% to 65% of overall NPP) (Table 3.2). Field observation from an earlier study at other mires in the same region (*unpublished data*), similar to DS, showed the total NPP ranged between 75 and 150 g C m^{-2} yr^{-1} with mosses and sedges contributing approximately equally to the total NPP (Nilsson and Bohlin, 2001). The variability in simulated NPP can be explained by the range of variability in soil climate and surface climate (Sagerfors, 2007; Nilsson *et al.*, 2008; Sagerfors *et al.*, 2008). Sedge NPP is more responsive to variability in climate, while moss growth is less.

3.5.2.2 Seasonal and inter-annual variability of simulated and measured NEP

The modified MWM captures the seasonal and inter-annual variability of NEP for DS reasonably well (Fig.3.4). Both simulated and tower measured NEP show a strong annual cycle with maximum daily carbon uptake ranging between 1.5 g C m^{-2} d^{-1} and 2.0 g C m^{-2} d^{-1} during the growing season and maximum carbon losses of 0.25 g C m^{-2} d^{-1} during the winter and spring season and up to 1.0 g C m^{-2} d^{-1} during the early autumn season (Fig.3.4).

The degree of agreement (d*) between simulated and observed NEP is 0.84, with a r^2 of 0.52 and a RMSE of 0.49 g C m^{-2} d^{-1}, of which 0.15 g C m^{-2} d^{-1} is systematic RMSE and 0.47 g C m^{-2} d^{-1} is unsystematic RMSE (Fig.3.5). The fact that unsystematic RMSE is much larger than systematic RMSE suggests that the modified MWM has a good measure of its potential accuracy in its current formulation, but the simulation can be improved by tuning the model's parameters. Compared to the statistical index based on the original MWM (section 5.1), the performance of the modified MWM has been improved and the RMSE was reduced by 42%.

Fig. 3.4: Comparison of measured and simulated daily NEP for 2001-2006 using the modified MWM.

Comparison of measured and simulated daily NEP, 2001-2006, using the MWM modified for poor-fen conditions and parameterized for a poor fen (Solid dark circles for the tower observed NEP and blank circles for the MWM simulated NEP). Positive NEP means carbon sinks; while negative NEP means carbon sources. In general, MWM can simulate the magnitude and direction of daily C cycling reasonably well and the inter-annul and seasonal variability of C fluxes were reproduced well.

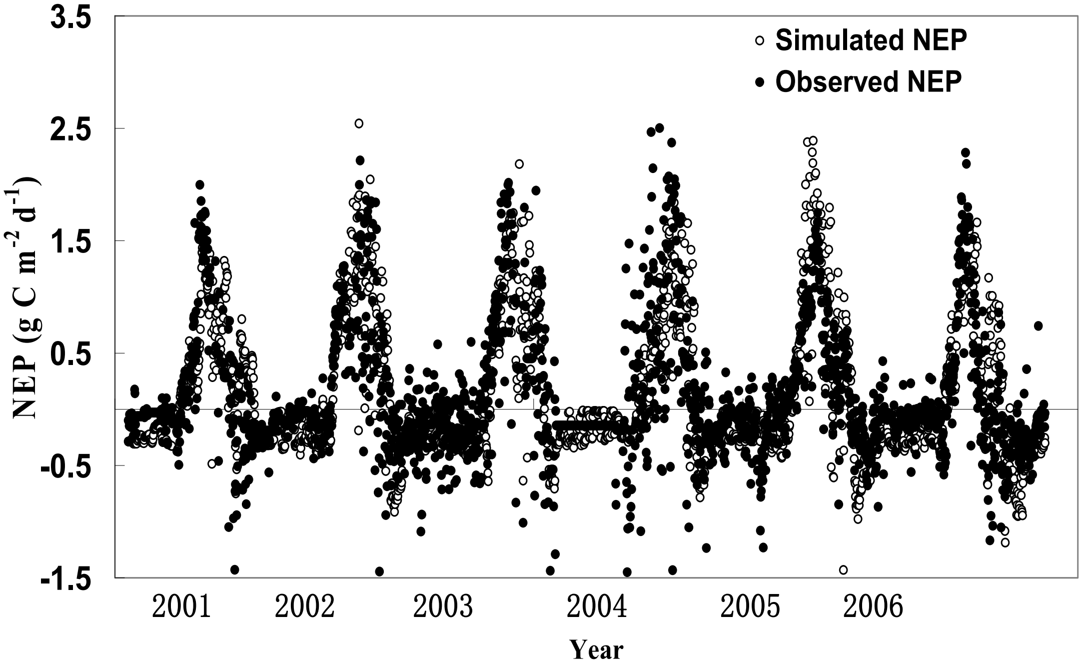


Fig. 3.5: Scatter plots of tower measured and simulated daily NEP for 2001-2006 using the modified MWM.

Scatter plots of tower measured and simulated daily NEP, 2001-2006, using the MWM modified and parametrized for poor fen conditions. The solid black line represents the least square regression line and the dashed black line is the 1:1 line (*i.e.* intercept=0). Positive value indicates carbon uptake; while negative value represents carbon losses. Compared with the performance of the original MWM, the performance of the modified MWM was greatly improved and the RMSE was reduced by 42%.

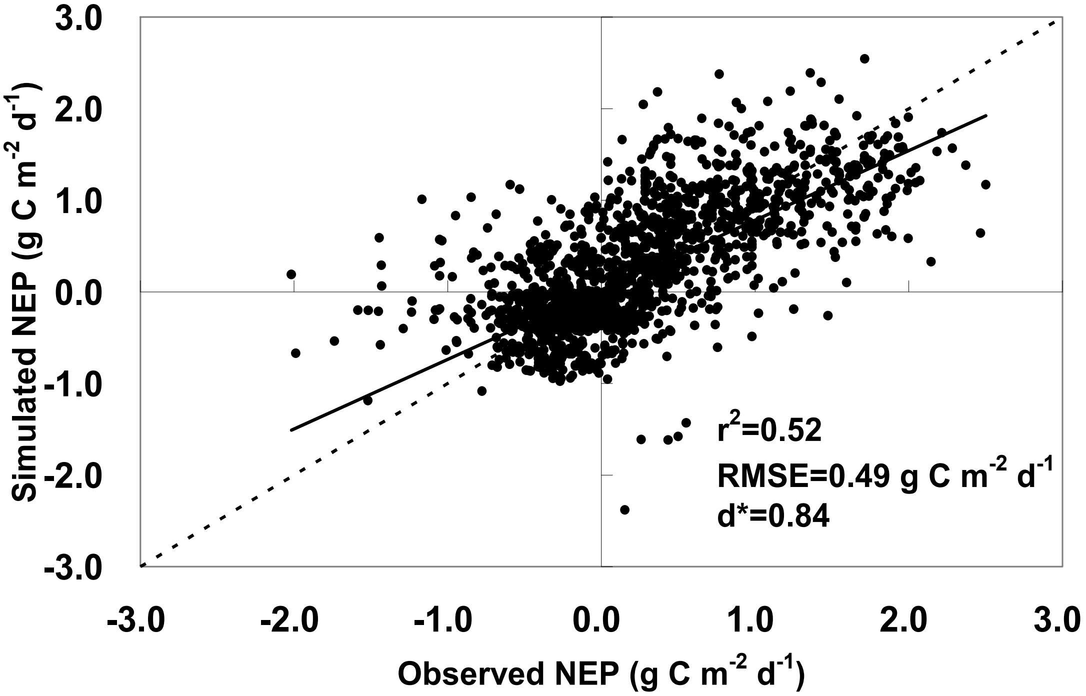
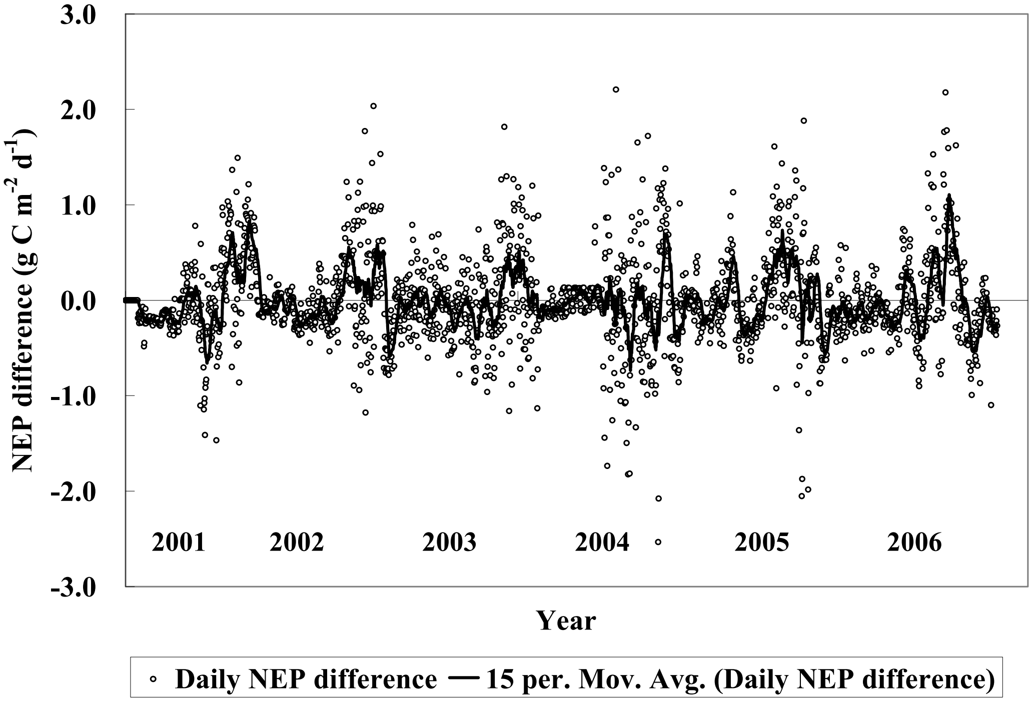


Fig. 3.6: The difference between tower measured and simulated daily NEP and the 15 days' moving average for 2001-2006 at DS.

The difference between tower measured and simulated daily NEP and the 15 days' moving average for that difference for 2001-2006 Blank black circles are the daily difference, while the solid black line is the 15 days' moving average for that difference. The positive difference means MWM overestimates daily NEP, while the negative difference means underestimation.



There appears no systematic bias in the simulated NEP compared to the daily tower measured NEP (Fig.3.6). Both overestimation and underestimation for daily NEP occur in the growing season. In general, the model estimates a higher positive daily NEP in the mid-growing season, while it estimates a lower positive daily NEP in the early and lately growing season. Most of the differences between the simulated and measured daily NEP are within ±1 g C m^{-2} d^{-1}.

3.5.2.3 The relationship between the CO_2 fluxes and environmental variables

The observation at DS shows that NEP and WTD are closely correlated (Fig.3.7). NEP reaches a maximum when WTD is 10 to 20 cm below peat surface, while NEP is reduced for either wetter or drier than optimal condition. The MWM produces a similar pattern between simulated NEP and WTD (Fig. 3.7). Yurova *et al* (2007) also simulated NEP in the same peatland with a different model. They described a maximum photosynthesis activity with a WTD within 10-20 cm based on data from 2001-2003, but the observation indicates that it is NEP, the difference between GPP and TER, reaches a maximum. When WTD is at or above the peat surface, presumably uptake is constrained due to limited oxygen diffusion (Tuittila *et al.*, 2004; Yurova *et al.*, 2007) and this reduces both GPP and TER. When WTD is too low to maintain maximum photosynthesis activity, GPP is reduced, but TER may be enhanced due to a thicker oxic zone (Waddington and Price, 2000; Bubier *et al.*, 2003b; Tuittila *et al.*, 2004; Moore and Basiliko, 2006). In the modified MWM, a soil water stress function was developed to represent these characteristics (section 3.2.2).

The observation for DS also shows that a close relationship exists between NEP and air temperature (Ta) (Fig. 3.8) that MWM successfully reproduces (Fig. 3.8). When Ta is between 0 and 20 ℃, NEP follows a pattern of approximately exponential growth. This may be because the increase in photosynthesis exceeds that in respiration in this range of temperatures, but Ta > 20 ℃, NEP may be decreased with increased temperature. The latter can be explained by a combination of restricted photosynthesis and enhanced decomposition. The restricted photosynthesis is caused by an enhanced closure of canopy stomata at a very high temperature.

3.5.3 Sensitivity analysis to changes in environmental conditions

There are two main purposes for the sensitivity analysis. First, it allows us to investigate what are the key sensitivities in the MWM. Second, it gives us the preliminary insight on how sensitive the carbon cycling of a poor fen is to the possible ranges of climate change. We conducted the sensitivity analysis by examining how the CO_2 fluxes changed with the changes in internal parameters, such as moss water content (Θ), sedge root depth (root_depth) and soil water stress index (ω), and extraneous parameters, such as temperature (T) and water table depth (WTD), within a range of hypothesized climate change scenario under the long-term equilibrium state. In this stand-alone version of the MWM, we impose changes in T and WTD directly.

In this sensitivity analysis the structure of the peatland ecosystem is constant, *i.e.* the current version of the MWM does not simulate vegetation dynamics due to the competitive advantage of one PFT over another, even though the ranges of physical conditions imposed in this sensitivity analysis, in some cases, goes beyond the functional range considered the hydrological and climatic "plant niche". The 6 years mean simulated NEP, GPP, AR and HR with the observations as inputs are used as the baseline and the response is expressed as a percentage change relative to this mean baseline. The changes in the above-mentioned key variables are imposed as a constant step change throughout the 6 years. To cover the potential climatic change (Meehl *et al.*, 2007), we imposed an anomaly in WTD between -10cm (representing wetter condition) and +20cm (representing drier condition) in increments of 5 cm and a T anomaly between -2 ℃ and 5 ℃ in increments of 1 ℃ on both air temperature (Ta) and peat temperature (Tsoil).

The GPP of mosses and sedges decreases as WTD increases or decreases (Table 3.3). Autotrophic respiration (AR) follows the same pattern as GPP. Since both GPP and AR follows the same pattern in response to WTD, so does NPP. The changes in HR follow the changes in oxic respiration in response to changes in WTD, since it is significantly larger than anoxic respiration. TER increases as WTD increases (*i.e.* drier). Since GPP is reduced and TER is increased with greater depth of WTD, NEP decreases dramatically as WTD drops- so much so that with a 15 and 20 cm WTD drawdown the poor fen switches to a carbon source to the atmosphere. This is also seen in the dry growing season conditions of 2006 (Sagerfors, 2007), when the growing season average WTD dropped ~15-20 cm below the lowest WTD since the start of measurements in 1995. The annual measured NEP dropped from ~40 g C m^{-2} yr^{-1} to 17 g C m^{-2} yr^{-1} during these conditions. Adding the carbon loss through emission of methane and discharge C-export to the NEP resulted in a mire C-balance not different from 0. TER decreases as WTD decreases (*i.e.* wetter). As with the drier situation, in the wetter settings the reduction of GPP is larger than that of TER, hence NEP is reduced.

Fig. 3.7: Relationship between daily NEP and summer water table depth for 2001-2006 at DS.

Relationship between daily NEP and summer water table depth (WTD during 2001-2006. Top panel: relationship between observed daily NEP and summer WTD; Bottom panel: relationship between MWM simulated NEP and summer WTD. Both the measured and simulated NEP reach its maximum when WTD is between 10 and 20 cm.

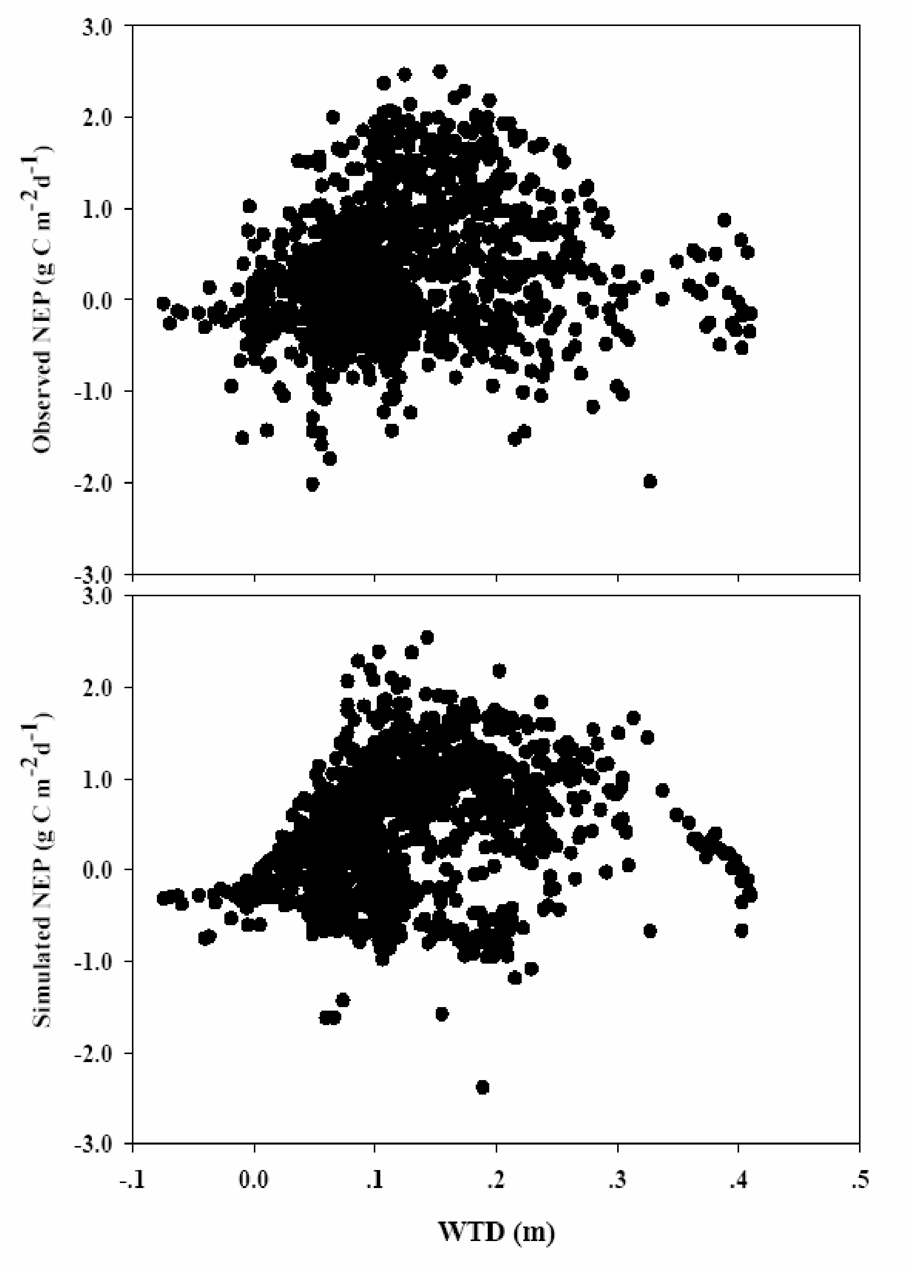


Fig. 3.8: Relationship between daily NEP and air temperature (Ta) for 2001-2006 at DS.

Relationship between daily NEP and air temperature (Ta). Top panel: relationship between observed NEP and Ta; Bottom panel: relationship between MWM simulated NEP and Ta.

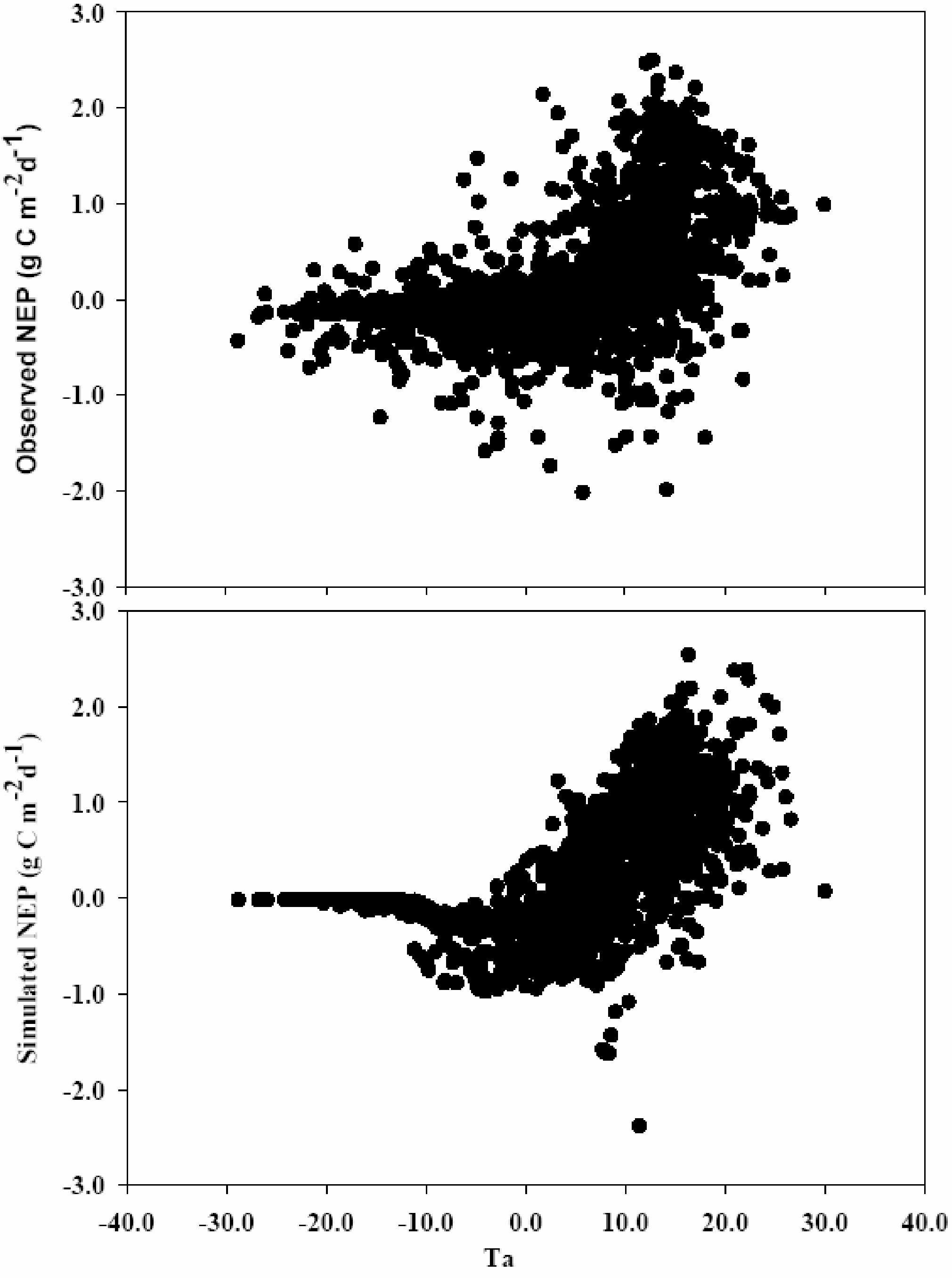


Table 3.3: Sensitivity of simulated GPP, TER and NEP to primary environmental variables and 3 key internal variables.

Sensitivity of simulated GPP, AR, NPP for moss and sedge, NEP, TER, OxicHR and AnoxicHR to primary environmental variables, *i.e.* water table depth (WTD) and temperature (Ta), and 3 key internal variables, *i.e.* moss water content (Θ), water stress index (ω) and sedge root depth (root_depth), expressed as a relative change in percentage to the base line fluxes calculated by the observed environmental variables. Changes in negative percentage indicate the decrease relative to the base line value, while changes in positive percentage indicate the increase. The changes in percentage is calculated by "(new value-base line)/base line ×100". Positive changes in WTD (hourly water table depth) means increase in water table depth, *i.e.* further down the peat surface, while negative changes in WTD means decrease in water table depth, *i.e.* closer to peat surface. Positive changes in Ta mean warmer temperature, while negative changes in Ta mean cooler temperature. Negative changes in ω mean higher water stress, while positive changes for lower water stress. The last 3 columns showed absolute C fluxes for GPP, TER and NEP when those changes were imposed. The unit for the C fluxes is g C m^{-2} yr^{-1}. Positive NEP means C uptakes by peatland, while negative NEP means C emission from peatlands. (See next page)

	Moss			Sedge			Total				C fluxes		
	GPP	AR	NPP	GPP	AR	NPP	NEP	TER	Oxic HR	Anoxic HR	GPP	TER	NEP
Base line	**152.8**	**79.4**	**73.4**	**295.8**	**215.4**	**80.4**	**44.4**	**404.1**	**94.6**	**14.7**	**448.5**	**404.1**	**44.4**
WTD (-10cm)	-39.0	-4.8	-75.9	-31.3	-11.7	-83.8	-186.9	-17.1	-49.4	45.2	296.5	335.1	-38.6
WTD (-5cm)	-17.0	-2.4	-32.8	-12.4	-5.6	-30.4	-55.4	-9.4	-24.6	-3.8	386.0	366.3	19.8
WTD (+5cm)	7.1	-0.3	15.1	2.3	1.5	4.2	-14.9	6.0	21.7	3.8	466.1	428.3	37.8
WTD (+10cm)	1.5	-4.2	7.7	-3.6	-1.2	-10.0	-92.3	8.1	41.4	-4.2	440.2	436.7	3.4
WTD (+15cm)	-14.2	-13.3	-15.2	-14.1	-5.3	-37.4	-214.8	7.9	60.7	-22.5	385.3	436.2	-50.9
WTD (+20cm)	-33.4	-29.8	-37.3	-26.4	-10.7	-68.5	-344.4	5.8	82.0	-48.9	319.3	427.7	-108.4
Ta (-3)	-8.4	-27.9	12.7	-31.2	-33.2	-26.0	193.2	-47.3	-89.1	-88.6	343.3	213.1	130.1
Ta (-2)	-5.4	-19.4	9.7	-20.6	-23.0	-14.2	47.5	-22.4	-23.4	-21.7	379.3	313.8	65.5
Ta (-1)	-2.6	-10.1	5.5	-10.2	-11.9	-5.8	27.9	-11.5	-12.2	-9.8	414.4	357.7	56.7
Ta (+1)	2.4	10.8	-6.8	9.9	12.5	3.0	-35.9	12.1	13.3	5.3	481.3	452.9	28.4
Ta (+2)	4.5	22.5	-15.0	19.0	25.3	2.0	-82.0	24.6	26.3	14.7	511.5	503.5	8.0
Ta (+3)	6.4	34.9	-24.5	26.9	38.4	-4.0	-145.0	38.0	39.5	39.9	537.8	557.8	-20.0
Ta (+5)	9.5	62.3	-47.8	41.0	66.1	-26.5	-339.0	70.8	79.2	131.0	584.1	690.2	-106.1
Θ (-20%)	0.1	7.3	-7.8	0.0	0.0	-0.0	-12.8	1.4	0.0	0.0	448.6	410.0	38.7
Θ (-10%)	0.1	4.1	-4.3	0.0	0.0	0.0	-7.1	0.8	0.0	0.0	448.6	407.4	41.2
Θ (+10%)	-0.1	-4.6	4.8	0.0	0.0	-0.0	8.0	-0.9	0.0	0.0	448.4	400.5	47.9
Θ (+20%)	-0.2	-9.6	10.1	0.0	0.0	-0.0	16.6	-1.9	0.0	0.0	448.2	396.5	51.8
ω (-20%)	-20.0	0.0	-41.7	-20.0	-9.7	-47.5	-112.4	-9.9	-21.6	10.9	358.8	364.3	-5.5
ω (-10%)	-10.0	0.0	-20.8	-10.0	-5.2	-23.0	-53.3	-5.2	-11.6	6.5	403.7	382.9	20.7
ω (+10%)	10.0	0.0	20.8	10.0	5.3	22.6	51.0	5.5	13.2	-11.1	493.4	426.4	67.0
ω (+20%)	20.0	0.0	41.7	20.0	10.1	46.7	100.2	11.2	27.7	-18.0	538.2	449.4	88.8
root_depth (-20%)	0.0	0.0	0.0	0.0	0.0	0.0	68.3	-7.5	-34.9	18.3	448.5	373.8	74.7
root_depth (-10%)	0.0	0.0	0.0	0.0	0.0	0.0	60.6	-6.7	-31.1	17.1	448.5	377.2	71.3
root_depth (+10%)	0.0	0.0	0.0	0.0	0.0	0.0	-26.8	2.9	26.5	-89.5	448.5	416.0	32.5
root_depth (+20%)	0.0	0.0	0.0	0.0	0.0	0.0	-219.9	24.1	118.1	-95.9	448.5	501.7	-53.2

Both GPP and AR increase with an increase in Ta, but the latter more, therefore NPP decreases with an increase in Ta. HR shows a positive response to Tsoil. Combining that NPP is reduced and HR is enhanced with an increase in Ta and Tsoil, NEP is reduced dramatically with an increase in Ta and Tsoil. Therefore, with an increase of 3 ℃, the poor fen becomes a source of CO_2 to the atmosphere. Both GPP and TER decrease with a decrease in Ta, but the latter is larger. Therefore, NEP increases with a decrease in Ta.

We imposed ±20% variations in the parameters describing the moss water content (Θ), water stress index (ω) and sedge root depth (root_depth). These were selected for analysis because they were the functions we modified for the fen version of the MWM. Caution has to be made that negative changes in ω means larger water stress in this system and positive means a smaller water stress. Mosses show a positive response to changes in Θ. NEP decreases as moss Θ decreases and NEP increases as moss Θ increases. Both mosses and sedges show a positive response to ω - *i.e.* GPP and NPP increase with an increase in ω and decrease with a decrease in ω. TER also increases with an increase in ω and decrease with a decrease in ω due to changes in oxic decomposition. Most of the response is in fresh litter decomposition. A -20% change in ω switches this system from a C sink to a C source. This indicates that this system is quite sensitive to soil water stress, especially drier than normal conditions. Changes in sedge root_depth only impact the soil decomposition: oxic decomposition increases with deeper sedge roots and decreases with shallower sedge roots, while anoxic decomposition decreases with deeper sedge roots and increases with shallower sedge roots. This sensitivity analysis shows sedge roots play a significant role in the CO_2 cycling of a poor fen, but more studies on root dynamics are needed to better quantify their effects.

3.6 Conclusions and prospects

With the modifications that we made to represent the differences between fens and bogs, the fen version of the MWM compared well with the observations. Low RMSE and high index of agreement and the patterns suggest that the fen version of the MWM captures adequately the magnitude and direction of the CO_2 fluxes and simulates the seasonal and inter-annual variability reasonably well. The modified MWM captures the inter-annual variability better than the bog version since the evergreen component is insignificant in the fen and this eliminated the drought induced ecological memory problem found for bogs in the year after a very dry summer (St-Hilaire *et al.*, 2008). However, methane emissions and total organic carbon (TOC) export constitute an important proportion of the mire total C-balance for poor fens (Granberg *et al.*, 2001; Nilsson *et al.*, 2001; Huttunen *et al.*, 2003; Worrall *et al.*, 2003; Nilsson *et al.*, 2008). At DS they were equivalent to between 16 and 29%, and 20% and 27%, respectively of the net annual C balance (Nilsson *et al.*, 2008). To simulate fully the annual C budget these additional fluxes need to be incorporated into the MWM.

Hilbert *et al*. (2000) stated that wet peatlands, *i.e.* fens, is less stable compared to bogs. We infer that the poor fen CO_2 cycling will be quite sensitive to climate change (Hilbert *et al.*, 2000), as confirmed by our sensitivity analysis. The analyses show that the DS fen can switch from C sinks to C sources from changes in temperature or WTD within the range examined. This is in agreement with the principles that the global and regional occurrence of peatlands can be inferred from the water balance equation, which in turn is tightly connected to the energy balance (Gedney and Cox, 2003; Gedney *et al.*, 2004). Sedge roots appear to be important for oxic decomposition, but few studies on their dynamics and association with peat decomposition through provision of oxygen to the saturated zone exist.

To investigate the responses of carbon cycling in northern peatlands to the projected climate change, both WTD and soil climate should be simulated under the projected climate conditions. Our plan is to couple the MWM to a wetland version of Canadian Land Surface Scheme (Wetland-CLASS) to simulate the WTD and soil climate. After validating the coupled CLASS-MWM against field measurements, CLASS-MWM will be ready to answer what-if questions and investigate how C cycling in northern peatlands may change under the future projected climate.

Connecting statement

To investigate the role of northern peatlands in coupled climate-carbon simulations, we have developed a peatland C cycling model, the McGill Wetland Model (MWM), as a function of soil climate and hydrology of peatlands. The MWM was originally developed and successfully evaluated to simulate the C dynamics of bogs. In Chapter 3, we modified MWM to simulate the CO_2 biogeochemistry of a minerotrophic poor fen, a peatland type common in boreal and sub-arctic landscapes. So far, the MWM has been successfully assessed in both bogs and fens, which are two general common-distributed peatlands.

Constructing a large-scale spatial model for peatland ecosystems, however, presents a number of unique challenges, one of which is to how to deal with the large variability that occurs over small scales (*e.g.* 0.5 to 3 m). Microtopography is a common feature of bogs. In models, spatial variability is considered either explicitly for each individual unit and the outputs averaged, referred to as flux upscaling, or implicitly by weighting model parameters by the fractional occurrence of the individual units, referred to as parameter upscaling. In Chapter 4, we use the MWM to examine how microtopography influences the C dynamics at the ecosystem level and determine the differences in ecosystem scale CO_2 fluxes based on flux upscaling and parameter upscaling.

Chapter 4 Does microtopography really matter in modelling ecosystem level carbon cycling of an ombrotrophic bog?

This chapter is based on a manuscript in preparation entitled:

Wu, Jianghua and others, Does Microtopography really Matter in Modelling Ecosystem Level Carbon Cycling of an Ombrotrophic Bog?

4.1 Introduction

Northern peatlands store ~ 450 G t soil carbon (C) (Gorham, 1991; Bridgham *et al.*, 2006), and they are significant natural sources of methane (Mikaloff-Fletcher *et al.*, 2004). The hydrology and biogeochemistry of peatlands are tightly coupled to climate (Charman, 2002; Gedney and Cox, 2003; Ise *et al.*, 2008), hence, the C cycling in northern peatlands is sensitive to climate variability and change (Roulet *et al.*, 1992b; Bridgham *et al.*, 2008). In order to examine this sensitivity to environmental change we have developed a process-based C model, the McGill Wetland Model (MWM), for peatlands that was successfully evaluated for northern bogs (St-Hilaire *et al.*, 2008). Constructing such a model for peatland ecosystems, especially for bogs, presents a number of unique challenges: one being how to deal with the spatial variability that occurs at small scales, *i.e.* 0.5 to 3.0 m (Belyea and Clymo, 2001; Belyea and Malmer, 2004). This is the scale of the microtopographic features of hummocks and hollows, or what Baird *et al.* (in press) refers to as the *SL1* (Spatial Level 1) scale.

The hydrology, vegetation structure, and functional biogeochemistry can vary considerably between hummocks and hollows (Waddington and Roulet, 1996; Malmer and Wallen, 1999; Weltzin *et al.*, 2001; Bubier *et al.*, 2006). For example, Waddington and Roulet (1996) found that CH_4 fluxes from the low relief lawns and hollows in an ombrotrophic peatland in central Sweden can exceed the fluxes from the high relief ridges by 10 to 50 times.

Hummocks and hollows are not isolated from each other, but comprise an organized entity. Though the formation of peatland microtopography is not fully understood (Belyea and Clymo, 2001; Nungesser, 2003; Rietkerk *et al.*, 2004), its existence is part of the complex adaptive structure of some peatlands (Belyea and Clymo, 2001; Belyea and Baird, 2006). The question we study in the present paper is “does the microtopography need to be treated explicitly or can the *SL1* scale (Baird *et al.*, in press) variability be treated implicitly by parameter and environmental variable weighting for ecosystem scale C simulations?”

There are two approaches to modelling the biogeochemical processes for systems that have considerable spatial variability (Anderson *et al.*, 2003). The explicit treatment is called flux upscaling (Viney and Sivapalan, 2004), where a model is run with explicit parameters and variables for each surface unit and then the outputs are weighted according to the fractional representation of each unit. The implicit treatment is called parameter upscaling (Arain *et al.*, 1999), where all of the parameters and variables for biophysical processes simulated in the model are weighted according to the fractional representation of each unit and a single ecosystem level output is produced (Arain *et al.*, 1999). While the flux upscaling is a more realistic representation of ecosystem heterogeneity, for regional and/or global climate studies the computational efficiencies of parameter upscaling are required. However, it is not always clear whether parameter upscaling can adequately capture the ecosystem level exchanges. This is especially true for peatlands with significant microtopography.

The small-scale variability in C cycling (Waddington and Roulet, 1996; Malmer and Wallen, 1999; Belyea and Clymo, 2001; Bubier *et al.*, 2003a), surface vegetation compositions and soil water chemistry (Charman, 2002; Bubier *et al.*, 2006) in ombrotrophic peatlands, *e.g.* bogs, results from the significant small-scale (0.5-3 m) spatial variability in surface and soil climate (Charman, 2002) because of hummock – hollow microtopography. This challenges the simulation of C cycling because water, temperature and plant community structure all exert control on C exchanges. Different measurement approaches capture this variation in C exchanges across scales. For instance, manual chambers and automatic chambers have been designed to measure the C fluxes for individual micro-sites (Bubier *et al.*, 2003b), while the eddy-covariance techniques apply to ecosystem scale C fluxes (Lafleur *et al.*, 2003). Individual site fluxes have been successfully scaled to give reasonable ecosystem level exchange rates when detailed areal representation of the dominant functional vegetation associations are accounted for (Riutta *et al.*, 2007). To date, ecosystem models of peatlands have used some average conditions, assuming *apriori* that the scale effects are small (Frolking *et al.*, 2002; St-Hilaire *et al.*, 2008), but this is an untested assumption introducing uncertainty to the ecosystem-level and/or regional-scale peatland C cycling (Moore *et al.*, 1998). It would be difficult, if not impossible, at present to explicitly represent micro-scale topographic influences in ecosystem models at the regional-scale and coarser scales.

We undertook a simulation study using the MWM to determine how different the model output was using the two methods for the Mer Bleue peatland in southern Ontario, Canada, a cool temperate raised bog composed of 70% hummocks and 30% hollows (Bubier *et al.*, 2003b; Lafleur *et al.*, 2003) . The MWM was configured for a hummock and a hollow separately, and then for a mixture of 70% hummocks and 30% hollows based on Mer Bleue observations (Lafleur, *et al.* 2003; Reimer, 2001). The simulated carbon fluxes based on the flux upscaling scheme and the parameter upscaling scheme were then compared with the measured carbon fluxes from an eddy-covariance tower at Mer Bleue.

The specific objectives of this study were to examine: (1) how the simulated C cycling varies between hummocks and hollows; (2) if either the hummock or hollow C fluxes alone represent the landscape-level C fluxes; and (3) whether the implicit spatial configuration of hummocks and hollows (*i.e.* parameter upscaling scheme) captures the ecosystem-level C fluxes sufficiently well enough for the output to be representative of the system. We show that despite the differences in individual components on the C exchange between hummocks and hollows, the difference scaled linearly so there was no significant difference between the spatially averaged outputs of the hummock and hollow simulations and the output of the parameter and input variable weighed simulations using the MWM.

4.2 Methods

4.2.1 Research site

This study was conducted on the Mer Bleue peatland, an ombrotrophic bog, located 10 km east of Ottawa, Ontario, Canada (45.41°N latitude, 75.48°W longitude, 69 m a.m.s.l). There have been continuous measurements of carbon, water and energy exchanges between peatland surface and the atmosphere since 1998 (Lafleur *et al.*, 2003; Roulet *et al.*, 2007) and in this study we used the data record from 1999 to 2006. Field measurements of soil climate, surface climate and water table depth, required for the MWM, were available, separately, for hummocks and hollows. In this study simulated net ecosystem production (NEP_{fu}: the flux upscaled NEP; or NEP_{pu}: the parameter upscaled NEP) are compared with the observed NEP (NEP_{ob}) from an eddy-covariance tower, representing a spatial average of ecosystem-level C fluxes. Details on the climate, ecosystem, and C biogeochemistry of Mer Bleue can be found in Bubier *et al.* (2006) and Roulet *et al.* (2007). Details on the measurements of the C fluxes can be found in Lafleur *et al.* (2003) and Roulet *et al*. (2007).

Mer Bleue peatland is a large (28 km^2) ombrotrophic bog (*i.e.* nutrients and water inputs by precipitation). The research site is located in the northern arm of Mer Bleue. The peatland surface here is slightly domed bog with a peat depth of 5-6m in the centre and 0.3 m at the margins. The microtopographic relief between mean hummock tops and the hollow bottoms is 25 cm (Lafleur *et al.*, 2003), with a range between 15 and 42 cm (Reimer, 2001). Hummocks represent approximately 70% of the surface and hollows 30% (Lafleur *et al.*, 2003). Water table is usually at or below the bottom of the hollows and it can vary considerably within the growing season (Lafleur *et al.*, 2003).

Significant differences in vegetation coverage, foliar biomass, leaf area index (LAI) and water chemistry exist between hummocks and hollows at Mer Bleue (Reimer, 2001; Bubier *et al.*, 2006). Reimer (2001) measured the vegetation characteristics across the microtopography and found no difference in moss coverage but a significant difference in shrubs between hummocks and hollows. For example, C. *calyculata* coverage is 30 to 100% on hummocks, but < 60% in hollows, while K. *angustifolia* has 5 to 80% coverage in hollows and < 40% on hummocks. Mean shrub height is 25 cm. Bubier *et al.* (2006) found a significant positive relationship between foliar and total vascular plant biomass and mean water table depth across hummocks and hollows. *Sphagnum* capitulum biomass averaged 166 g m^{-2} for hollows and 155 g m^{-2} for hummocks, while foliar biomass for shrubs averaged 143 g m^{-2} for hollows and 171 g m^{-2} for hummocks. LAI for vascular vegetation averaged 1.1 for hollows and 1.7 for hummocks (Bubier *et al.*, 2006).

4.2.2 Data processing for model runs

Hourly micrometeorological measurements are required to run the MWM (Fig.4.1). The simulation for hummocks and hollows uses common environmental inputs: air temperature (Ta), precipitation (P), photosynthetic photon flux density (PPFD), net radiation (Rn), relative humidity (RH), atmospheric pressure (Pair) and atmospheric CO_2 concentration ([CO_2]). We have assumed there are no significant differences between hummocks and hollows for these common environmental inputs. The specific inputs for hummocks or hollows are peatland surface temperature (Surf T), three layers of peat soil temperature (Soil T1, Soil T2, Soil T3) and water table depth (WTD). These are unique to the two settings or are weighted for the parameter upscaling scheme. In addition to the environmental inputs site-specific parameters such as peat depth, foliar biomass for mosses and shrubs, vegetation root biomass, V_{cmax25} (the maximum velocity of Rubisco carboxylation at 25 ℃) are applied (Table 4.1). In addition to the site-specific parameters, a complementary data set containing model parameters based on studies reported in the literature served for all sites within a range of general northern peatlands types (refer the Table 1 in St-Hilaire *et al.*, 2008).

Fig. 4.1: The configuration diagram for hummocks and hollows, representing the flux upscaling scheme.

This diagram shows the configuration of hummocks and hollows separately for MWM simulation. MWM was implemented for hummocks and hollows separately. Then the simulated hummock and hollow CO_2 fluxes were spatially averaged to obtain the ecosystem-level CO_2 fluxes using $F=0.7*F_{hum}+0.3*F_{hol}$.

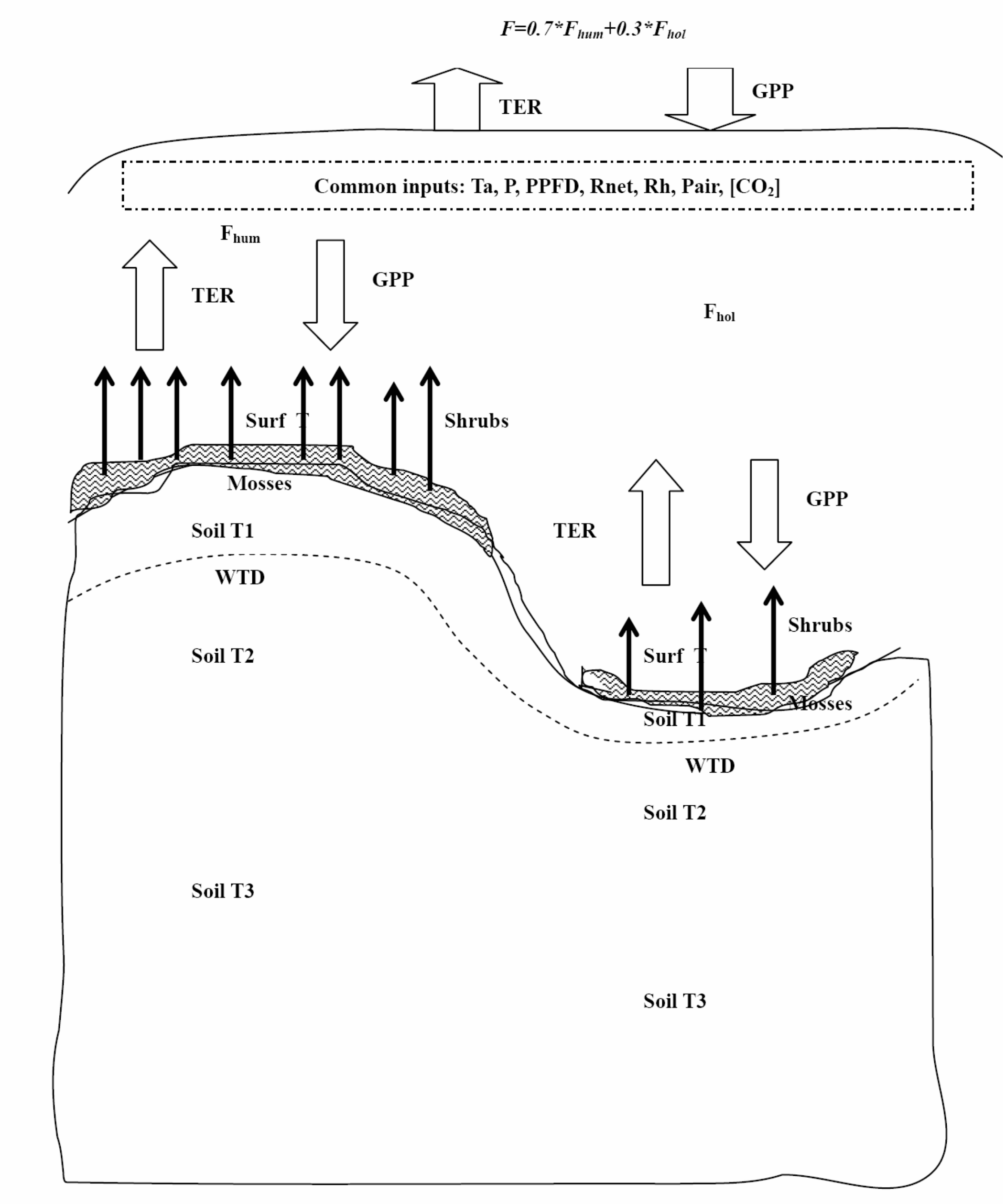


Table 4.1: Initialization and parameter values for the configuration of hummock simulation, hollow simulation and parameter upscaling for McGill Wetland Model (MWM). pu*: for parameter upscaling scheme.

Parameter	Hummock	Hollow	pu*	Units	Description	Reference/Source
Values for Model Parameters at 25°C						
J_{max}:V_{max}	1.67	1.67	1.67	-	ratio	(Medlyn *et al.*, 2002)
Mosses						
V_{cmax25}	6	6	6	μmol $m^{-2}s^{-1}$	max carboxylation rate (spring)	(Williams and Flanagan, 1998)
	14	14	14	μmol $m^{-2}s^{-1}$	max carboxylation rate (summer)	
	7	7	7	μmol $m^{-2}s^{-1}$	max carboxylation rate (autumn)	
R_{d25}	0.946	0.946	0.946	μmol $m^{-2}s^{-1}$	dark respiration rate	(Harley *et al.*, 1986)
Shrubs						
V_{cmax25}	17	17	17	μmol $m^{-2}s^{-1}$	max carboxylation rate	N.T. Roulet unpublished
Initial site specific parameters						
frac	48.7	48.7	48.7	%	biomass to carbon ratio	T.R. Moore unpublished
B_{moss}	140	180	168	g biomass m^{-2}	moss capitula biomass	(Moore *et al.*, 2002)
$B_{min\ foliar}$	175	100	122.5	g biomass m^{-2}	min shrub foliar biomass	
$B_{max\ foliar}$	350	200	245	g biomass m^{-2}	max shrub foliar biomass	
LAI_moss	1.3	1.6	1.44	m^2/m^2	initial moss leaf area idex	(Bubier *et al.*, 2006)
LAI_shrub	1.05	0.6	0.9	m^2/m^2	initial shrub leaf area index	(Bubier *et al.*, 2006)
Root_shrub	250	200	235	g biomass per m^2	Initial shrub root biomass	
Litter_shrub	120	100	114	g biomass per m^2	Initial shrub litter biomass	
B_{stem}	0.003	0.003	0.003	$m^3\ m^{-2}$	shrub sapwood volume	
PD_0	6	6	6	m	initial peat depth	(Roulet *et al.*, 2007)

We used a “gap-filled” micrometerological data obtained at hummocks and hollows respectively for 1999-2006 as the environmental inputs. Due to power outage, instrument failure and other unexpected interruption, gaps exist in the observed input data. We undertook a similar gap-filling procedure for all the hourly environment drivers measured at hummocks and hollows, with the exception of the water table. The half-hour gaps of environmental drivers were filled by their previous 5 hours’ average value. In addition, since the water table depth measured at hummocks was considered more reliably than that for hollows, we developed an empirical relationship between observed hollow and hummock WTD and used it to gap fill the hollow water table for periods when needed. Since the depth of the peat temperatures required for the MWM did not match exactly the nine depths (0.01 to 2.5 m) of measurement of the peat temperature in the hummock and hollows we linearly interpolated to obtain the temperatures between the depths of observation. The MWM has an hourly time step so we averaged the half hour data to derive the hourly data.

4.2.3 Upscaling method

For the flux upscaling the MWM was run for a hummock (hummock NEP: NEP_{hum}) and a hollow (hollow NEP: NEP_{hol}) with the environmental site specific input variables, parameters and initialization in each case. Then a flux upscaled NEP, NEP_{fu}, was calculated by weighting the NEP_{hum} by 0.7 and the NEP_{hol} by 0.3. For the parameter upscaled NEP, NEP_{pu}, the MWM was run once with the input variables, parameters and initialization weighted to represent 0.7 hummock and

0.3 hollow. The NEP_{fu} and NEP_{pu} were then compared with the NEP_{ob} ,the eddy-covariance measured flux.

4.2.4 Evaluation tools

4.2.4.1 Observed carbon fluxes

At the Mer Blue peatland, the carbon, water and energy fluxes between peatland surface and the atmosphere have been continuously measured since May 1998 using the eddy-covariance (EC) technique (Lafleur *et al.*, 2003; Roulet *et al.*, 2007). 8 years of data, Jan. 1 1999 to Dec. 31, 2006, were used in this study, which is consistent with the evaluation period used in St.-Hilaire *et al.* (2008). We used the same terminology for gross primary production (GPP), total ecosystem respiration (TER), and net ecosystem production (NEP) as proposed by Chapin III *et al.*(2006). We used the observed net ecosystem exchange (NEE) to represent the NEP (NEP= -NEE). The observed NEP_{ob} and derived TER_{ob} and GPP_{ob} were used for comparison of C fluxes at the ecosystem-level. The Fluxnet-Canada measurement and processing protocols were used in our flux data processing (Protocols for EC Flux Measurement Protocols, August 2003: http://www.fluxnet-canada.ca/).

On average, 42% of the half-hour NEE measurements were removed from each year's data due to instrument malfunction or quality control (Lafleur *et al.*, 2003; Roulet *et al.*, 2007). Gaps were filled using the same procedure for each calendar year of the 8-year period as described in Lafleur *et al.* (2003) and Roulet *et al.* (2007). First, any gaps less than 2 hours were filled by linear interpolation. Secondly, after this first step of gap-filling, the gap-filling techniques for longer period of gaps were divided into a period of 5 cm soil temperature of < 0 ℃ and a period of 5 cm soil temperature of > 0℃. For the former case, missing NEE was filled with the mean NEE from 200 consecutive half-hour measurements or weekly mean NEE. For the latter case, an exponential relationship was derived between the nighttime half-hour NEE (assumed to be equivalent to TER) and 5 cm soil temperature. Estimates of TER using this relationship were adjusted to match seasonal variation in TER using a multiplier found by regressing modelled values against measured values for 200 consecutive half-hour measurements (between 7 days and 2 months) moving through the year in increments of 40 half-hours (Roulet *et al.*, 2007). Nighttime missing NEE was filled by this relationship. Finally, daytime estimate of GPP when 5 cm soil temperatures were > 0℃ were calculated by adding modelled TER, using the same relationship derived above, to measured NEE. Then a rectangular hyperbolic relationship between GPP and photosynthetically active radiation (PAR) was derived for 15 June to July 15 of each year. GPP computed from this relationship was then adjusted to match the seasonal variation in GPP using the same procedure for TER above. In the end, daytime missing NEE was filled by subtracting the modelled TER from the computed GPP.

4.2.4.2 Evaluation criteria

The primary statistical indices used in this study for evaluating how closely the modelled C fluxes followed the measured C fluxes are the Root Mean Square Error (RMSE) and the coefficient of determination (r^2) (St-Hilaire *et al.*, 2008). We also used an index of agreement (d*) developed by (Willmott, 1985). d* ranges between 0 and 1, where 0 indicates no agreement and 1 indicates perfect agreement between simulated and observed values. Moreover, a Student's t-test was used to examine whether the simulated C fluxes (*i.e.* GPP, TER and NEP) were significantly different between hummocks and hollows and a single factor ANOVA and a Kruskal-Wallis non-parametric test were applied to examine whether there were significant differences among NEP_{fu}, NEP_{pu} and NEP_{ob}. All the statistical hypothesis tests were conducted with α=5%. The *p* value shown in Table 4.3 and 4.6 means the probability of a chance at which the deviation can reach this big or bigger based on the null hypothesis, *i.e.* equal means. Therefore, if $p \geq \alpha$, it means that we have sufficient statistical evidence to state that there is no significant difference among sample means; if $p < \alpha$, it means that we have sufficient statistical evidence to state that there is significant difference among sample means.

4.2.5 Simulated CO_2 fluxes

MWM calculates moss and shrub photosynthesis and autotrophic respiration (AR) separately, and are added to get hummock and hollow GPP (GPP_{hum}/GPP_{hol}) and AR (AR_{hum}/AR_{hol}). The sum of fresh litter decomposition, oxic and anoxic decomposition gives heterotrophic respiration (HR) and AR+HR is TER. In the MWM, TER is subtracted from GPP to get NEP. We used a positive NEP to represent the CO_2 sequestration from the atmosphere, while a negative NEP represents the CO_2 emission to the atmosphere.

4.3 Results

4.3.1 Microtopographic effects on individual CO_2 fluxes

MWM simulations showed that significant variations existed between hummocks and hollows in individual components that make up NEP (Table 4.2). Statistical comparisons for individual components of NEP between hummocks and hollows were given in Table 4.3. GPP was not statistically different between hummocks and hollows (p>0.75), but moss and shrub contributions to total GPP were significantly different (p<0.0001) (Table 4.3). Shrubs played a dominant role in the hummock CO_2 cycling, while mosses dominated the hollow CO_2 cycling. TER was also significantly different between hummocks and hollows (p<0.0001) with $TER_{hum} > TER_{hol}$. As a consequence, NEP was also significantly different (p<0.0001) between hummocks and hollows, with NEP_{hol} significantly > NEP_{hum}. The simulated differences in NEP_{hum} and NEP_{hol} resulted from the difference in TER that was due to differences in the mean water table position and plant community structure. The deeper water table in the hummock increased HR over that of the hollow. While there were significant differences in the relative importance in moss and shrub GPP to overall GPP between hummocks and hollows, the magnitude of the total GPP was not significantly different. As a consequence neither NEP_{hum} nor NEP_{hol} alone approximated the measured ecosystem level NEP_{ob} (Fig.4.2). This was most apparent during the growing season, though for some years both simulated NEP_{hum} and NEP_{hol} were smaller than NEP_{ob}.

4.3.2 Comparison of simulated ecosystem-level C fluxes with observed ones

To assess the differences between flux and parameter upscaling we compared the mean daily simulated and observed GPP, TER and NEP for the period 1999 to 2006 (Fig.4.3). Overall, the seasonal patterns and inter-annual variability was reproduced by both upscaling schemes. The magnitude and sign of the daily CO_2 exchanges was simulated reasonably well, however neither upscaling scheme captured the peak daily C flux in the summer well, both consistently underestimated the growing season peak by ~ 1 g C m^{-2} d^{-1}.

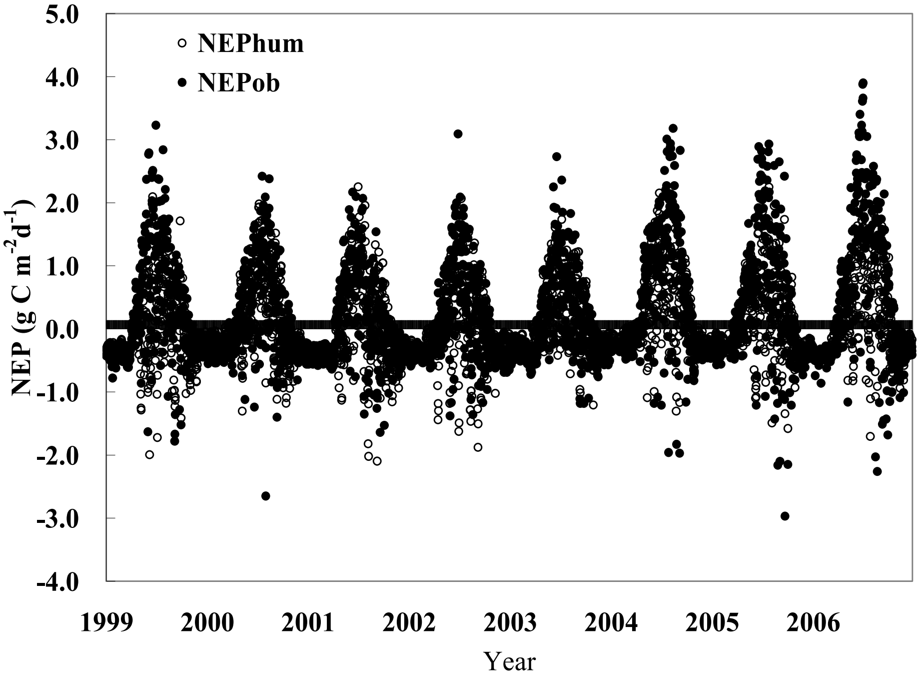
Scatter plots between the simulated and observed CO_2 fluxes showed that both flux and parameter upscaling did an equally acceptable job (Fig. 4.4 and 4.5). Both approaches did not capture the peak GPP and TER fluxes indicating a systematic bias of the ecosystem-scale GPP and TER, but this is not due to the upscaling. This was an inherit problem from the MWM (St-Hilaire *et al.*, 2008). We tested the idea proposed by St-Hilaire *et al.* (2008), *i.e*. relaxation of the upper limits of standing foliar biomass. Even when we increased the upper limit by 100%, the problem was not solved (data not shown). The r^2 and d* found between flux and parameter upscaled, and observed GPP and TER indicated close agreement and the RMSE were < 0.7 and < 0.5 g C m^{-2} d^{-1}, respectively (Fig. 4.4).

The comparisons for NEP upscaling indicated that there was no systematic overestimation or underestimation introduced by either upscaling scheme (Fig.4.5), but comparison statistics (*i.e.* r^2 and d*) indicated that NEP had poorer agreement than its component parts, GPP and TER, yet the RMSE (< 0.5 g C m^{-2} d^{-1}) was similar.

We separated out the overall statistical indices for daily GPP, TER and NEP comparison into the year-to-year statistical indices for 1999-2006 (Table 4.4). For the combined data set (*i.e.* all years) there was no statistically significant difference (p>0.35) between flux and parameter upscaling estimates of the daily fluxes (Table 4.3), but there were small variations in performance among years (Table 4.4)**.** Willmott's d* exceeded 0.88 for all years and was frequently near unity. Although the RMSE varied between flux components and between years, more importantly, it did not differ greatly between the two upscaling formulations. We also examined the differences among the flux and parameter annual upscaled GPP, TER and NEP and observed ones (Table 4.3 and 4.5). For all 8 years, both ANOVA and nonparametric Kruskal-Wallis statistical test showed that there were no significant differences among observed, flux and parameter upscaled C fluxes (*i.e.* GPP, TER and NEP) (p>0.30) (Table 4.3). The year-to-year absolute differences, however, did exist (Table 4.5). Of the 8 years, flux upscaled fluxes were always a little bit smaller than parameter upscaled ones. But the differences between upscaled and observed fluxes showed random pattern rather than systematic bias (Table 4.5). All the discrepancies were within the acceptable level of 5-15%.

Fig. 4.2: Daily comparison between simulated (a) hummock NEP (NEPhum) and (b) hollow NEP (NEPhol), and the observed NEP (NEPob) for 1999-2006. Open circles are for simulated NEP (NEPhum, NEPhol) and filled circles for NEPob. Positive NEP means CO_2 sequestration by peatland, while negative means CO_2 emission to the atmosphere.

(a) NEP$_{hum}$ vs. NEP$_{ob}$



(b) NEP$_{hol}$ vs. NEP$_{ob}$

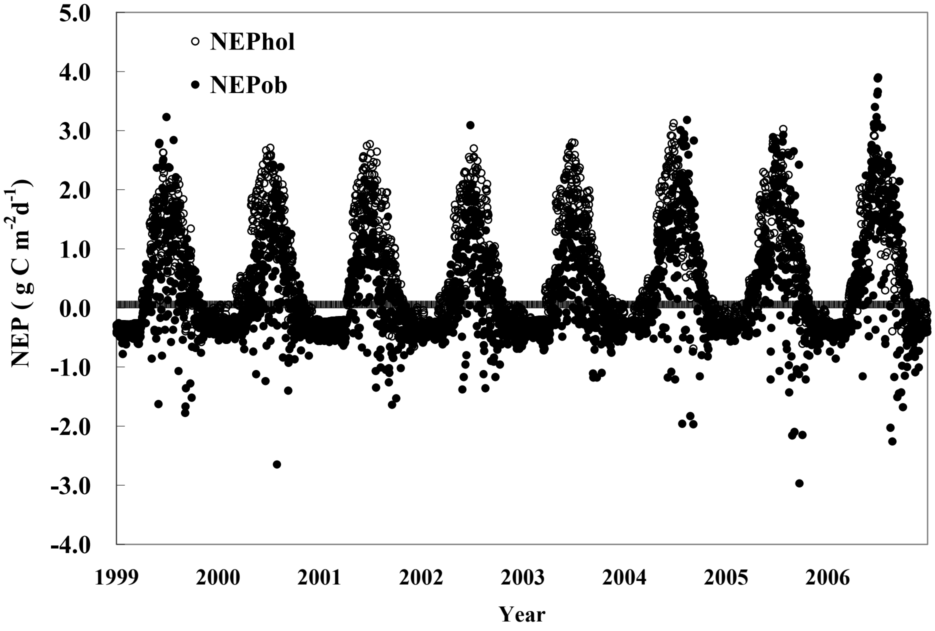
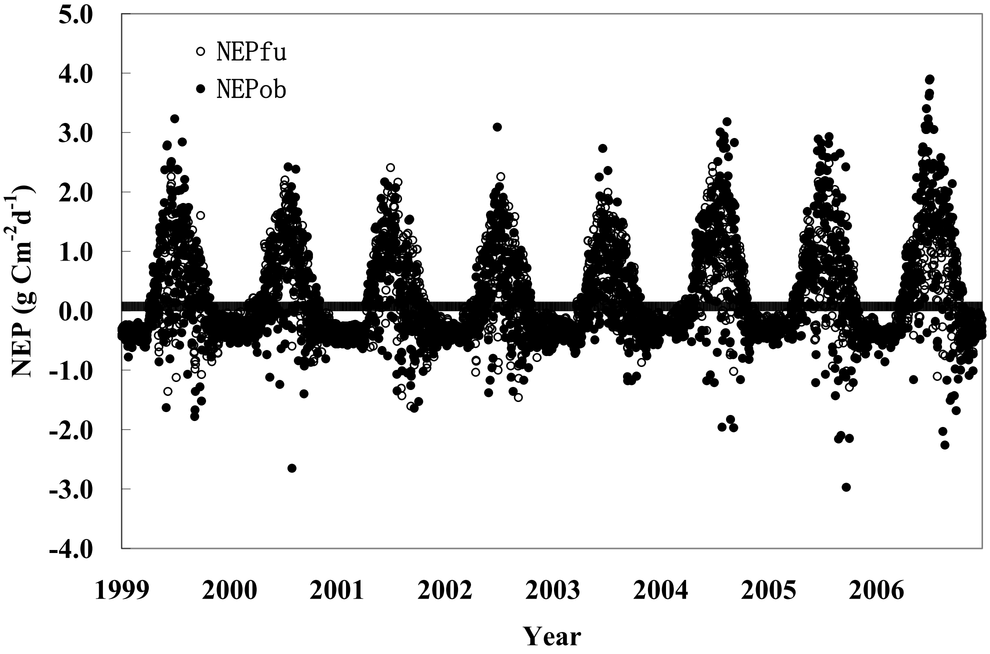


Fig. 4.3: Daily comparison between simulated NEP based on (a) flux upscaling (NEP_{fu}) and (b) parameter upscaling (NEP_{pu}) and observed NEP (NEP_{ob}). Open circles are for simulated NEP (NEP_{fu}, NEP_{pu}) and filled circles for NEP_{ob}.

(a) NEP_{fu} vs. NEP_{ob}



(b) NEP_{pu} vs. NEP_{ob}

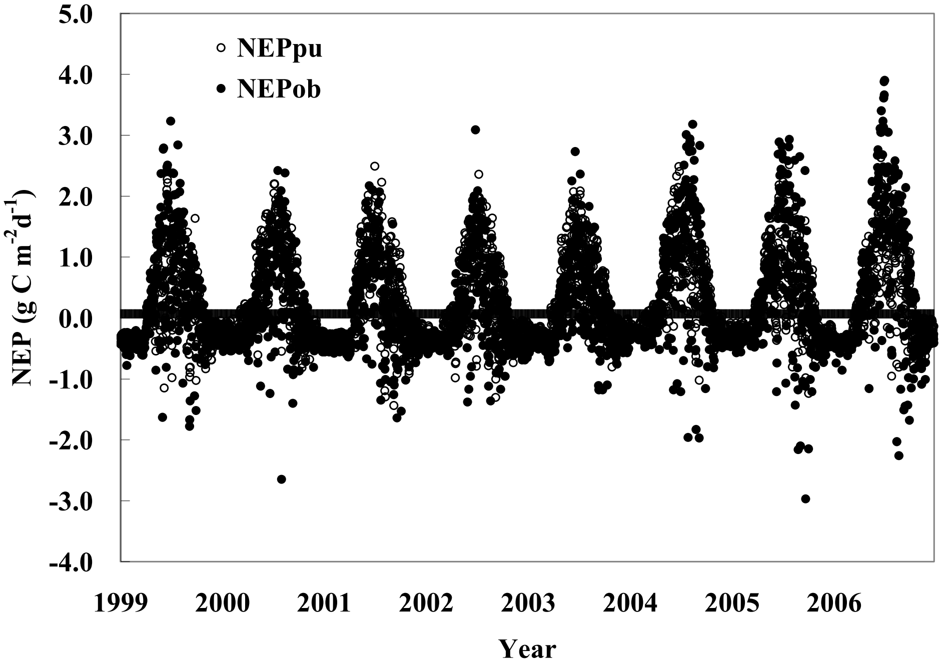
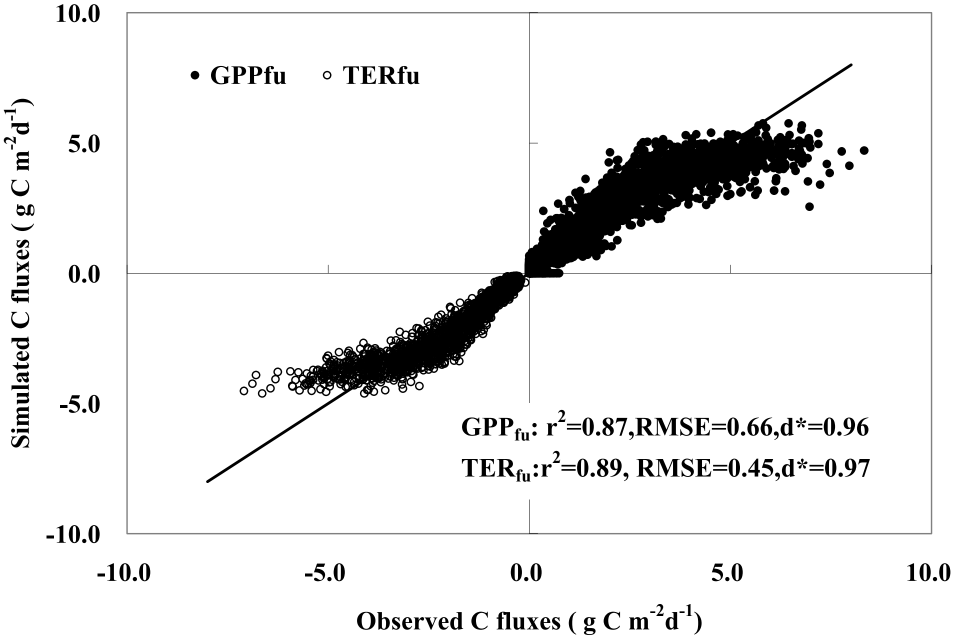


Fig. 4.4: The 1:1 scatter plots between the observed (x-axis) and simulated daily GPP/TER (y-axis) based on (a) flux upscaling and (b) parameter upscaling scheme. Open circles are for TER and filled circles for GPP.

(a) Flux upscaling



(b) Parameter upscaling

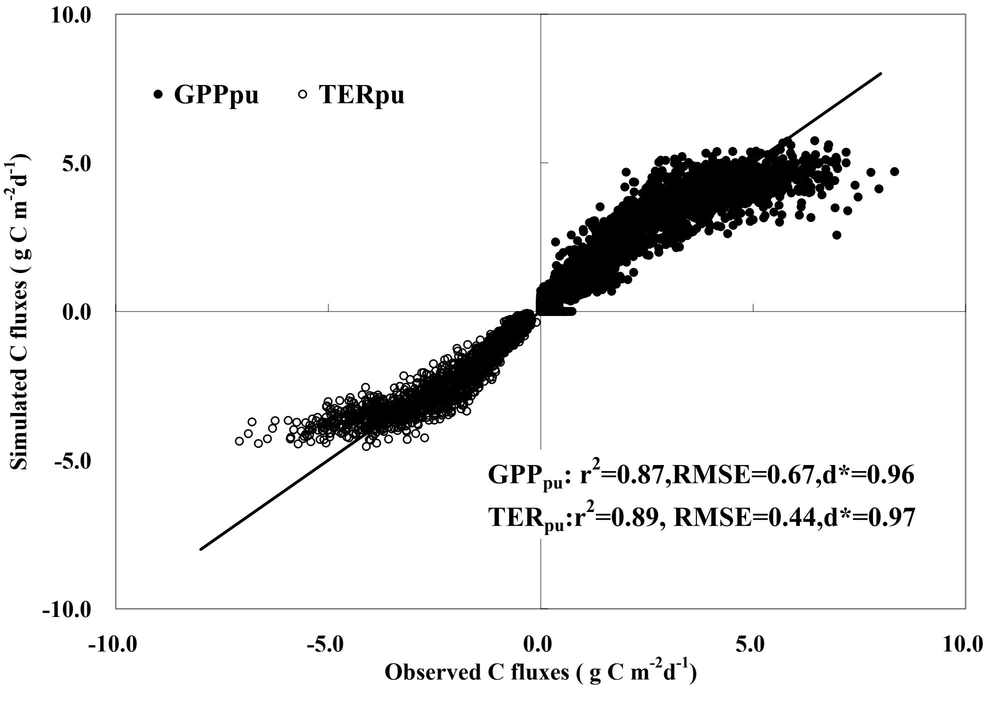
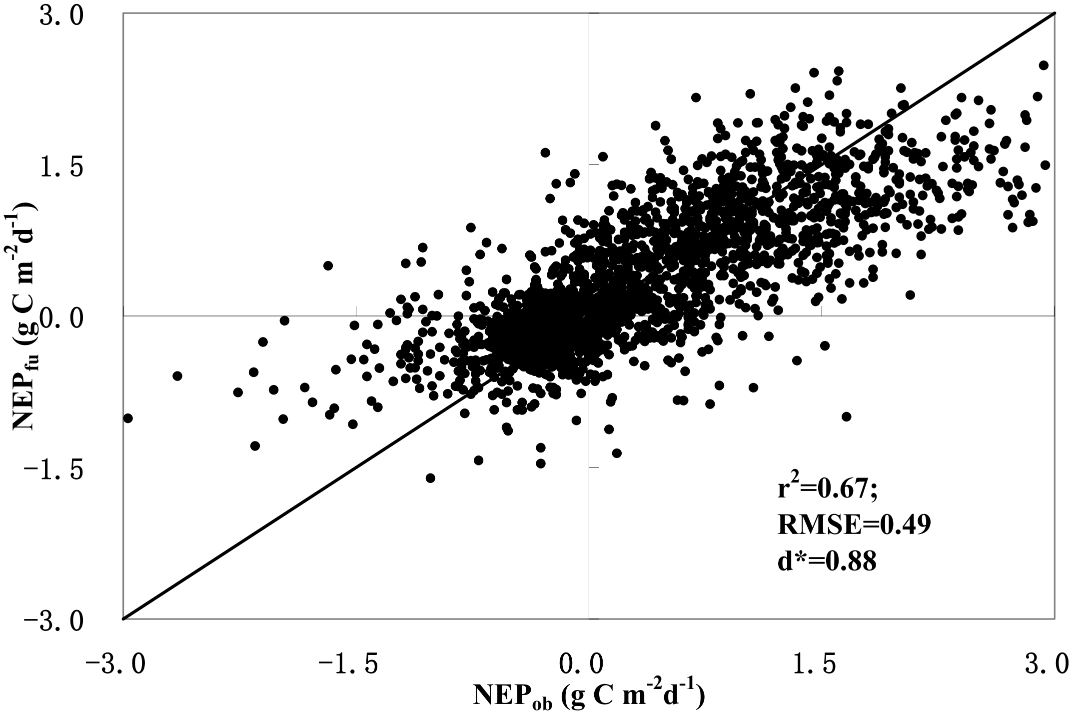


Fig. 4.5: The 1:1 scatter plots between the observed (x-axis) and simulated daily NEP (y-axis) based on (a) flux upscaling and (b) parameter upscaling scheme.

(a) Flux upscaling



(b) Parameter upscaling

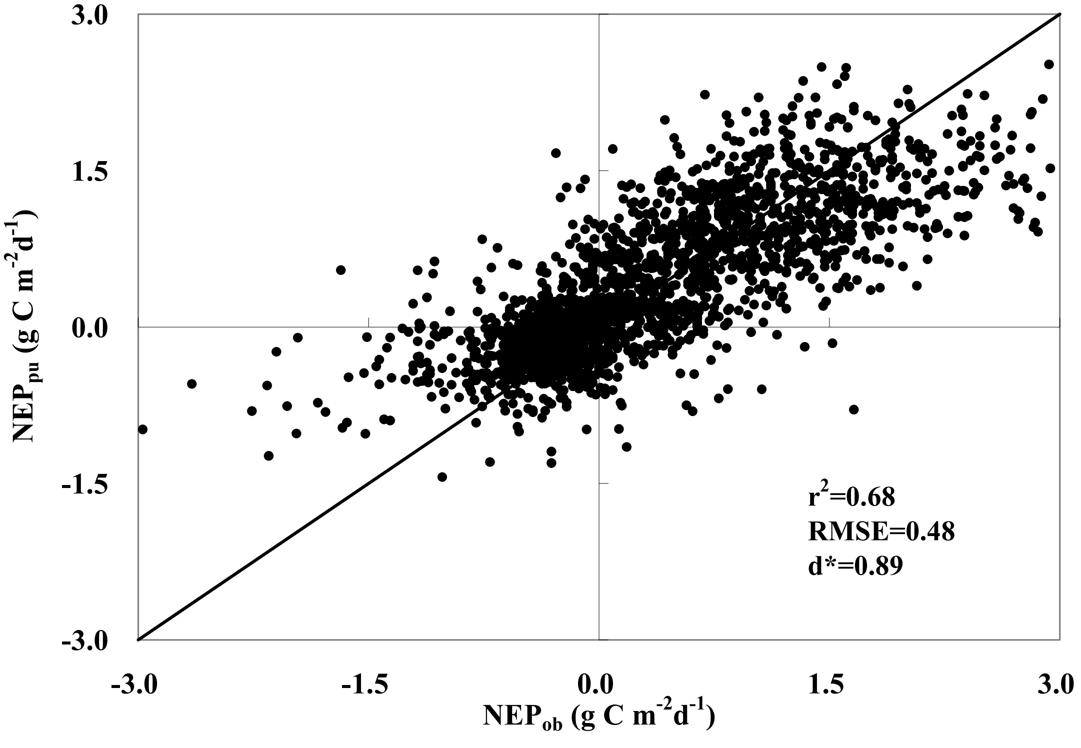


Table 4.2: The C fluxes (GPP, TER and NEP) for hummocks and hollows simulated by MWM for 1999-2006. The fraction of GPP from moss and shrub for hummocks and hollows is also shown.

Total GPP = MossGPP + ShrubGPP; Total TER = MossAR + ShrubAR + OxicHR + AnoxicHR; NEP = GPP + TER. (Unit: g C m^{-2} yr^{-1}).

Year	**GPP**						**TER**		**NEP**	
	GPP$_{hum}$	**GPP$_{hol}$**	**MossGPP$_{hum}$** %	**MossGPP$_{hol}$** %	**ShrubGPP$_{hum}$** %	**ShrubGPP$_{hol}$** %	**TER$_{hum}$**	**TER$_{hol}$**	**NEP$_{hum}$**	**NEP$_{hol}$**
1999	583.99	590.97	31.16	61.57	68.84	38.43	-602.65	-445.14	-18.65	145.83
2000	584.67	604.30	36.35	65.19	63.65	34.81	-550.25	-372.85	34.43	231.45
2001	620.37	616.09	30.59	60.52	69.41	39.48	-627.54	-423.36	-7.17	192.73
2002	603.93	613.24	35.10	63.90	64.90	36.10	-611.05	-418.82	-7.12	194.42
2003	622.07	626.23	33.45	62.64	66.55	37.36	-590.63	-396.52	31.44	229.70
2004	665.56	665.66	33.76	62.59	66.24	37.41	-599.91	-405.45	65.64	260.21
2005	663.83	659.43	31.71	61.11	68.29	38.89	-640.63	-431.39	23.20	228.04
2006	658.05	660.65	31.99	61.67	68.01	38.33	-619.96	-435.86	38.09	224.78
Average	625.31	629.57	33.01	62.40	66.99	37.60	-605.33	-416.17	19.98	213.40

Table 4.3: Statistical student's t test significance *p* values for the C components between hummocks (hum) and hollows (hol), and the ANOVA significance *p* values among flux (fu) and parameter upscaled (pu) and observed (ob) C fluxes at 95% confidence level.

Components between hum and hol	p	Components among fu,pu and ob [b]	p	Components between fu and pu	p
GPP	0.79	GPP(ANOVA)	0.64	GPP	0.80
Moss_GPP	4.15×10^{-12} [a]	TER(ANOVA)	0.90	TER	0.49
Shrub_GPP	8.05×10^{-9} [a]	NEP(ANOVA	0.30	NEP	0.39
TER	6.17×10^{-7} [a]				
NEP	1.81×10^{-8} [a]				

a indicates a significant difference; *b* indicates a non-parametric Kruskal-Wallis test was also applied to confirm the ANOVA test results, where the *p* values are 0.85,0.83,and 0.26 for GPP,TER and NEP respectively.

Note: All the statistical hypothesis tests were conducted with α=5%. In this table the *p* value means the probability of a chance at which the deviation can reach this big or bigger based on the null hypothesis, *i.e.* equal means. Therefore, if $p \geq \alpha$, it means that we do not have sufficient statistical evidence to reject the null hypothesis; if $p < \alpha$, it means that we do not have sufficient statistical evidence to accept the null hypothesis.

Table 4.4: General statistics for the comparisons between simulated C fluxes (GPP, TER and NEP) based on flux (fu) and parameter upscaling (pu) scheme and observed C fluxes (GPP, TER and NEP). RMSE is the root-mean-square-error with the unit of g C m^{-2}d^{-1} and d* is the Willmott agreement index.

	GPP_{fu}		GPP_{pu}		TER_{fu}		TER_{pu}		NEP_{fu}		NEP_{pu}	
Year	*RMSE*	*d**	*RMSE*	*d**	*RMSE*	*d**	*RMSE*	*d**	*RMSE*	*d**	*RMSE*	*d**
1999	0.84	0.95	0.83	0.95	0.57	0.96	0.59	0.95	0.50	0.87	0.48	0.89
2000	0.67	0.95	0.68	0.95	0.46	0.95	0.45	0.96	0.43	0.89	0.45	0.88
2001	0.65	0.96	0.65	0.96	0.41	0.97	0.41	0.97	0.46	0.88	0.46	0.88
2002	0.59	0.97	0.60	0.97	0.41	0.97	0.38	0.98	0.48	0.86	0.47	0.87
2003	0.66	0.96	0.66	0.96	0.43	0.97	0.41	0.97	0.43	0.87	0.45	0.87
2004	0.57	0.98	0.58	0.98	0.35	0.98	0.38	0.98	0.53	0.88	0.53	0.88
2005	0.51	0.98	0.52	0.98	0.36	0.98	0.38	0.98	0.47	0.91	0.46	0.91
2006	0.81	0.96	0.81	0.96	0.61	0.96	0.49	0.97	0.58	0.89	0.57	0.90
Average	0.66	0.96	0.67	0.96	0.45	0.97	0.44	0.97	0.49	0.88	0.48	0.89

Table 4.5: The differences among the annual C fluxes (GPP, TER and NEP) simulated by flux (fu) and parameter upscaling (pu) scheme and observed ones (ob) for 1999-2006.

Unit for C fluxes: g C m^{-2} yr^{-1}

Year	**GPP_{fu}-GPP_{pu}**	**GPP_{ob}-GPP_{fu}**	**GPP_{ob}-GPP_{pu}**	**TER_{fu}-TER_{pu}**	**TER_{ob}-TER_{fu}**	**TER_{ob}-TER_{pu}**	**NEP_{fu}-NEP_{pu}**	**NEP_{ob}-NEP_{fu}**	**NEP_{ob}-NEP_{pu}**
1999	-2.70	60.15	57.45	-11.21	-26.30	-37.50	-13.91	33.86	19.95
2000	-4.56	-127.33	-131.89	-6.14	65.72	59.58	-10.70	-61.61	-72.31
2001	-3.80	-75.81	-79.60	-10.91	25.03	14.12	-14.71	-50.77	-65.48
2002	-4.63	-95.69	-100.33	-10.62	55.24	44.62	-15.26	-40.45	-55.71
2003	-4.49	-128.70	-133.18	-8.84	52.19	43.35	-13.33	-76.51	-89.84
2004	-5.43	17.42	12.00	-6.71	-26.26	-32.96	-12.13	-8.83	-20.96
2005	-3.98	25.77	21.79	-9.56	-20.04	-29.60	-13.54	5.73	-7.81
2006	-3.76	113.36	109.61	-6.55	-59.93	-66.48	-10.31	53.43	43.13
Average	-4.17	-26.35	-30.52	-8.82	8.21	-0.61	-12.99	-18.14	-31.13

Table 4.6: Student's t test significance *p* values for the comparison between flux and parameter upscaling for different hypothesized mixtures of hummocks and hollows.

Mixture scenarios: "40+60%" means 40% hummocks and 60% hollows

Mixture scenarios	***p* for GPP between fu and pu**	***p* for TER between fu and pu**	***p* for NEP between fu and pu**
40+60%	0.86	0.27	0.51
50+50%	0.83	0.25	0.49
60+40%	0.82	0.24	0.46
70+30%	0.80	0.49	0.39
80+20%	0.85	0.23	0.39
90+10%	0.91	0.25	0.35

Note: All the statistical hypothesis tests were conducted with α=5%. In this table the *p* value means the probability of a chance at which the deviation can reach this big or bigger based on the null hypothesis, *i.e.* equal means. Therefore, if $p \geq \alpha$, it means that we do not have sufficient statistical evidence to reject the null hypothesis; if $p < \alpha$, it means that we do not have sufficient statistical evidence to accept the null hypothesis.

4.3.3 The effect of the microtopographic mixtures on the upscaling

The results in the previous section were based on the empirical observation of microtopographic mixture ratios, *i.e.* 70% hummocks and 30% hollows, in Mer Bleue. It is likely that peatlands could develop various mixture ratios of hummocks and hollows at different stages of their development (Belyea and Clymo, 2001). To investigate if the same results hold with different microtopographic mixtures, we simulated the NEP for both flux and parameter upscaling based on 5 hypothesized mixtures of hummocks and hollows, *i.e.* 40+60%, 50+50%, 60+40%, 80+20% and 90+10% respectively. The student's t tests showed that regardless of the microtopographic mixtures there were no statistically significant difference between flux and parameter upscaled CO_2 fluxes (GPP, TER and NEP), where $p > 0.80$ for GPP, >0.23 for TER and >0.35 for NEP (Table 4.6) .

4.4 Discussions

The objectives of this study were to evaluate the importance of hummock and hollow microtopography for modelling CO_2 exchange from northern peatlands, and specifically to compare flux and parameter upscaling methods of ecosystem level modelling. The results from our study are encouraging and allow us to address the following important questions.

4.4.1 How does microtopography influence the differences in CO_2 exchanges between hummocks and hollows?

Our modelling results showed that the simulated GPP was not significantly different between hummocks and hollows, but NEP was because of differences in TER (Table 4.2, 4.3). There are several processes that may contribute to this. Hummocks are generally drier than hollows with the water table ~ 25 cm deeper relative to the peat surface. The drier hummock environment is beneficial to growth of vascular vegetation, particularly woody shrubs due to the aeration of roots, while the growth of mosses may be suppressed due to a lower availability of water at the surface (Weltzin *et al.*, 2001; Strack and Price, 2009). The lower water table in hummocks also provides a thicker oxic zone, enhancing the mass of peat and litter subjected to oxic decomposition. Drier conditions increase the production of more readily decomposed vascular litter compared to that of moss litter, which is considerably less decomposable. These differences in biophysical characteristics, especially those favouring decomposition, result in the higher simulated annual NEP in hollows than hummocks. Additionally, because the acrotelm is much thicker in hummocks than hollows, due to differences in water table depth, residence time of organic matter in acrotelm of hummocks is longer – *i.e.* in hummocks the transfer of organic matter to the catotelm, where the decomposition rate of organic matter is about one thousand times slower than that in acrotelm (Belyea and Clymo, 2001), is longer. As a result, the amount of decomposition in hummock acrotelm would be greater than in the hollow acrotelm, hence peat accumulation is less.

It is reassuring that the MWM reproduces this critical difference in TER between hummocks and hollows but it also illustrates a limitation of the MWM in its current configuration. The MWM is a 1-d single column model that does not change its surface elevation relative to the water table due to peat accumulation. The link between the hydrology and change in the height of a peatland is included in some models that are used for much longer time scale simulations of peatland development (Hilbert *et al.*, 2000), but in models for use in climate simulations this presents a very difficult challenge as it alters the boundary conditions not only for C cycling but also the radiation, energy and water fluxes. Further, over time the larger C accumulation in hollows would make them grow closer to hummocks reducing the microtopographic relief between them that, in turn, leads to a reduction in lateral flow from the hummocks to the hollows making the hummocks and hollows, respectively, relatively wetter and drier. This feedback gives bogs some of its self-regulating capability (Belyea and Baird, 2006) and maintains the microtopography pattern - *i.e.* what Belyea and Clymo (2001) refer to as "a dog on a leash" relationship. The consequences of this self regulation represent a significant further challenge for the inclusion of peatlands in regional to global scale coupled climate-carbon assessments and possible ways of addressing this challenge will be explored in Section 4.3.3.

4.4.2 Does parameter upscaling capture adequately ecosystem-level C exchanges?

Firstly, comparison of simulated GPP, TER and NEP based on flux or parameter upscaling with the measured GPP, TER and NEP at the Mer Bleue peatlands shows that there is little difference in the final result. The comparison of the daily exchanges shows similar magnitude and direction between the two approaches (Fig. 4.4), and both share the same inability to capture maximum peak summer daily C fluxes. The comparisons reveal no systematic overestimation or underestimation and statistical comparisons indicate no significant differences between flux and parameter upscaling. Secondly, there is little relative difference in performance between the two upscaling approaches for all flux components compared to observed fluxes (Table 4.4) even though there is considerable year-to-year variability in each of the components (Table 4.5). Therefore, we conclude that the method of upscaling does not introduce significant bias and in the case of the hummock – hollow micro-scale variability we can simulate the system adequately using the much less computational intensive parameter upscaling.

Our study in a bog peatland provides a near 'ideal' opportunity to compare the effectiveness of flux and parameter upscaling in capturing the ecosystem-level biogeochemical processes because the scale of heterogeneity (0.5 to 3 m) (Baird *et al.*, in press) is much smaller than the footprint of the measurements of ecosystem level exchange (Lafleur *et al.*, 2003; Roulet *et al.*, 2007). As a result we can implement 'data rich' flux and parameter upscalings and compare the simulated outputs with appropriate ecosystem scale observations of the spatially integrated fluxes. In many landscapes and ecosystems the patchiness of heterogeneity occurs at larger scales (100 m to 10 km) and is at or beyond the spatial scale of measurements (Arain *et al.*, 1999; Anderson *et al.*, 2003). In addition, because of the patchiness of the landscape in other ecosystems it is not as easy to constrain the simulations for model parameters, characterization of the ecosystem, and the input variables.

Both flux and parameter upscaling, however, have been successfully applied in other ecosystems to characterize the sub-grid heterogeneity in biophysical and biochemical properties, such as soil, vegetation and topographic characteristics (Blyth *et al.*, 2004; Yeh and Eltahir, 2005). However, most studies apply only one of flux or parameter upscaling. One example of this kind of approach relevant to the problems of scale in hydrology is the appropriateness of statistical characterization, rather than explicit treatment of small scale variability in capturing the integrated response at coarser scales (Wood *et al.*, 1992). Probability distribution functions (PDF) inferred from field observation or existing datasets can characterize effective parameters to represent the spatial heterogeneity in water table position (Yeh and Eltahir, 2005), soil water content (Gedney and Cox, 2003), soil infiltration capacity (Wood *et al.*, 1992), and topographic characteristics (Warrach *et al.*, 2002). Finding such statistical functions to characterize peatland heterogeneity, and more importantly, to tie the functions to some physical and ecological conditions that would allow them to change appropriately with changing climate is going to be a significant challenges for the peatland-climate communities (Baird *et al.*, in press; Frolking *et al.*, in press).

4.4.3 Implications and prospects

Northern peatlands are mainly distributed at high latitude where future climate is projected to experience more severe changes than other regions (IPCC, 2007). More specifically, high latitudes will be subject to warmer and possibly drier climate. In northern peatlands, hydrology and biogeochemistry are tightly linked with climate (Charman, 2002; Gedney and Cox, 2003; Ise *et al.*, 2008). For example, this fact is integral to the feedback between biological and hydrological processes operating near the bog surface, which permits the persistence of the microtopographic arrangement between hummocks and hollows. What is not known is how the microtopographic configuration and biogeochemical processes in northern bogs will respond to climate change.

In our study we used a known distribution of microtopography (*i.e.* 70% hummocks and 30% hollows) to examine issues of parameter scaling, but will our results be valid under the future projected climate? Paleoecological evidence shows that bog microforms experience both vertical adjustment and shifts in lateral extent when climate changes (Blackford, 2000; Belyea and Clymo, 2001; Bauer, 2004). Thus, we need to further examine the nature of the relationship between the local vertical and/or horizontal expansion or contraction with respect to the fluctuation of surface wetness under the climate change (Belyea and Clymo, 2001; Belyea and Baird, 2006). Our simulation analysis based on the different hypothesized mixtures of hummocks and hollows (Table 4.6) has shown that regardless the mixture ratios there is no significant difference between flux and parameter upscaled CO_2 fluxes. However, for other trace gas exchanges such as methane, this is likely not to be the case since changes in soil moisture and vegetation communities, resulted from changes in the mixtures of hummocks and hollows, can result in 1 to 2 orders of magnitude changes in fluxes (Baird *et al.*, in press).

If the relative spatial coverage of hummocks and hollows is altered due to the climate change, what will be the new spatial configuration? There are three possibilities: 1) the microtopographic configuration is maintained as it is; 2) the microtopographic configuration is maintained, but the spatial mix of features changes; and 3) the microtopography is lost or replaced by some completely new configuration. A way to examine the spatial dynamics of hummocks and hollows is to establish a spatial statistical distribution function of certain biophysical predictors, for example water table depth and vegetation composition, within a large scale of simulation unit (for example, one pixel for a global circulation model (GCM)) (Baird *et al.*, in press) and link it with the climate dynamics. Then we only need to examine how the statistical distribution function changes with climate change.

To develop this statistical parameterization we need to use spatially explicit models that couple the dynamic links among hydrology, vegetation, and microtopography (*e.g.* Belyea and Clymo, 2001; Rietkerk *et al.*, 2004; Belyea and Baird, 2006). The lateral hydrological dynamics will be the key to addressing this issue because the redistribution of water between hummocks and hollows drives differences in nutrients, soil chemistry and thus vegetation. This means that we must consider the cross-scale links of hydrology and vegetation (Belyea and Baird, 2006) because vegetation composition at the micro-scale will, through effects on peat hydrochemical and physical properties, affect the water movement and nutrient status in the whole landscape-scale peatland (Baird *et al.*, in press).

Connecting statement

In our previous work and Chapter 3 we developed and evaluated the MWM for both bogs and fens. MWM captured the magnitude and direction of CO_2 fluxes for Mer Bleue bog and Degero Stormyr fen well and reproduced the seasonal and inter-annual variability. To run the MWM, the key inputs, such as surface climate and soil climate including soil temperature, soil moisture and water table depth can be obtained either from field measurements or from the simulation of a land surface model, such as the wetland version of Canadian land Surface Scheme (CLASS3W).

In Chapter 5, we couple MWM to CLASS3W and evaluate this coupled model, called CLASS3W-MWM, for the Mer Bleue bog and the Degero Stormyr fen by comparing the simulated peatland climate and C fluxes with the observations. Further, we examine the sensitivity of C cycling in northern peatlands to changes in temperature, precipitation and atmospheric CO_2 concentration.

Chapter 5 Simulating the carbon cycling of northern peatlands using a coupled land surface climate and wetland carbon model (CLASS3W-MWM)

This chapter is based on a manuscript in preparation entitled:

Wu, Jianghua and others, Simulating the carbon cycling of northern peatlands using a coupled land surface climate and wetland carbon model (CLASS3W-MWM).

5.1 Introduction

Uncertainties in terrestrial C cycling have been recognized as one of the key uncertainties in projecting the future climate (Huntingford *et al.*, 2009). Terrestrial and oceanic C cycling has recently been included in the present global C-coupled climate model (Denman *et al.*, 2007). Global C-coupled climate models all show a positive feedback (Cox *et al.*, 2000; Friedlingstein *et al.*, 2006; Denman *et al.*, 2007), but the magnitude varies considerably. Uncertainties exist because several significant physical processes and terrestrial ecosystems have not been included in the current generation of C-coupled climate model: nitrogen (N) cycling, fire and peatlands (Denman *et al.*, 2007). In our previous work we developed and evaluated a peatland carbon model, the McGill Wetland Model (MWM), for bogs (St-Hilaire *et al.*, 2008) and fens (Chapter 3) based on the observed weather. In this paper, we couple MWM to a land surface scheme and then evaluate this coupled model for bogs and fens. We also investigate, with the coupled model, the sensitivity of two peatland forms, a bog and a fen, to changes in temperature, precipitation and atmospheric CO_2 concentration.

Northern peatlands store ~450 G t carbon (C) (1 G t C=10^{15} g C) (Gorham, 1991; Bridgham *et al.*, 2006) because net primary production (NPP) in northern peatlands has been larger than decomposition for thousands of years (Clymo *et al.*, 1998; Roulet *et al.*, 2007). Covering only 3-6% of global land (Matthews and Fung, 1987; Lehner and Doll, 2004), peatlands store ~1/3 of the global terrestrial soil C (Gorham, 1991). Wetlands are also the largest natural emitter of methane and northern peatlands contribute about 10% of wetland emissions (Mikaloff-Fletcher *et al.*, 2004).

The hydrology and biogeochemistry of northern peatlands are tightly coupled to climate (Charman, 2002; Belyea and Malmer, 2004; Bridgham *et al.*, 2008; Ise *et al.*, 2008). Northern peatlands are located at high latitudes where future climate is expected to have greatest change (Meehl *et al.*, 2007), hence, climate change could result in significant changes in C cycling (Bridgham *et al.*, 2008). Northern peatlands are generally subdivided as bogs and fens (Bridgham *et al.*, 1998). Bogs receive water and nutrients solely from precipitation, whereas fens receive additional water and nutrients from surface and groundwater sources. The differences in water and nutrients inputs between bogs and fens result in differences in soil chemistry, hydrological regime, nutrient availability and vegetation structures (Bridgham *et al.*, 1998; Chapin *et al.*, 2004). These ecological differences lead to the differences in biogeochemical processes and greenhouse gas fluxes, and bogs and fens should respond to climate change differently (Bridgham *et al.*, 2008). Field manipulations suggest that fens are more sensitive to climate change than bogs, especially warming temperature and water table drawdown (Bridgham *et al.*, 2008).

To examine the sensitivity of C cycling in northern peatlands in response to a climate change, we developed a process-based C cycling model, McGill Wetland Model (MWM) (St-Hilaire *et al.*, 2008 and Chapter 3). MWM can simulate the vertical CO_2 exchanges between peatlands and the atmosphere. To examine the C cycling under the future climate, the soil climate, including soil temperatures, soil moisture and water table depth (WTD), need to be simulated, therefore, we coupled MWM with a land surface climate model, the wetland version of Canadian Land Surface Scheme (CLASS3W) (Verseghy, 1991; Verseghy *et al.*, 1993; Comer *et al.*, 2000; Letts *et al.*, 2000). This coupled model is referred as CLASS3W-MWM. However, we need to evaluate for how well CLASS3W-MWM can simulate the present CO_2 cycling.

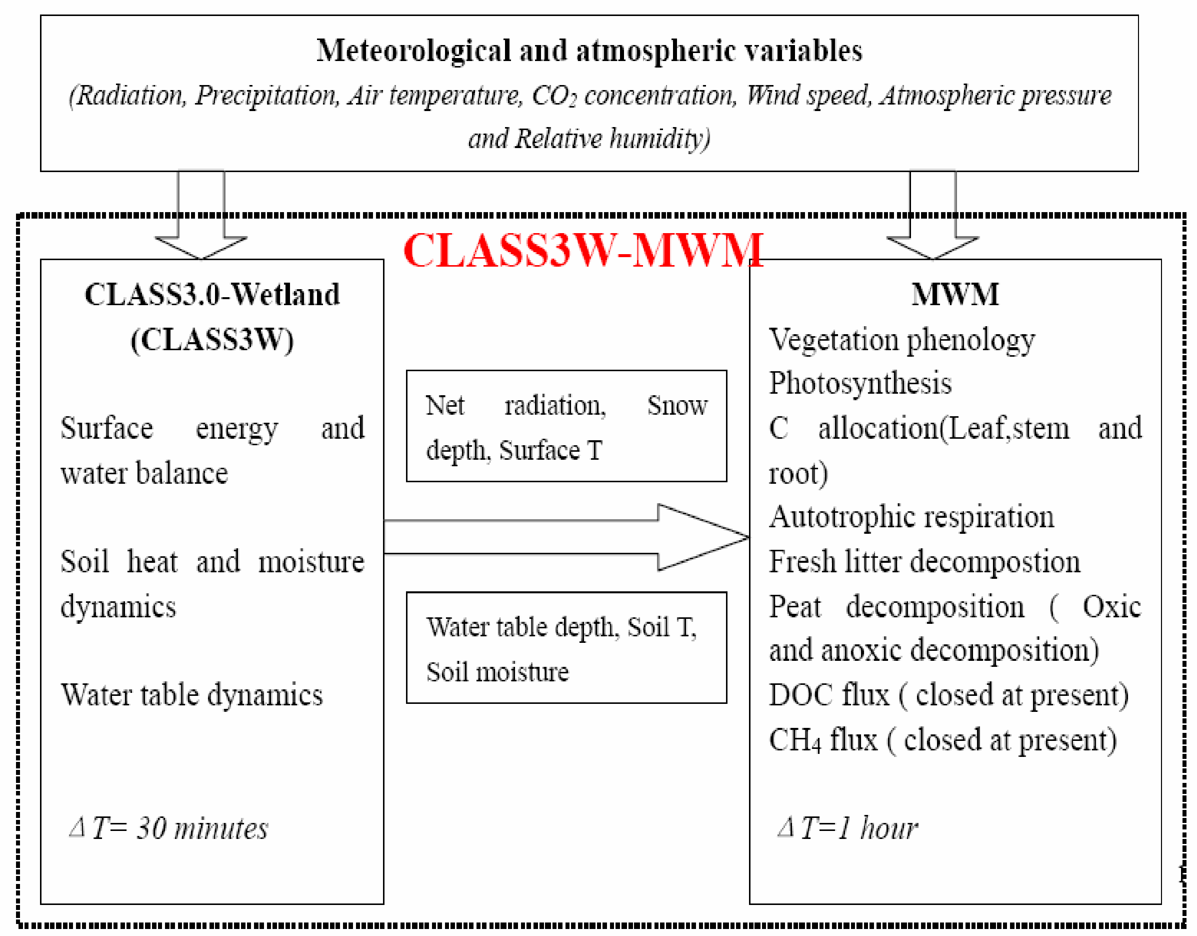
Our objectives are: (1) to evaluate CLASS3W-MWM for a bog peatland and a fen peatland; and (2) to investigate the sensitivity of C cycling in northern peatlands to changes in temperature, precipitation and atmospheric CO_2 concentration. We evaluated CLASS3W-MWM at Mer Bleue (MB), an ombrotrophic bog in Eastern Canada (Lafleur *et al.*, 2001; Lafleur *et al.*, 2003; Roulet *et al.*, 2007), and Degero Stormyr (DS), a minerotrophic poor fen in Northern Sweden (Sagerfors, 2007; Sagerfors *et al.*, 2008). The evaluation based on the comparison between the simulated and observed C fluxes shows that the magnitude, direction, inter-annual and seasonal variability of C fluxes are captured reasonably well for both fens and bogs. Our sensitivity analysis shows that fens are more sensitive to changes in temperature and precipitation than bogs. Moreover, increases in temperature can switch both bogs and fens from C sinks to C sources, but changes in precipitation did not change the direction of the C exchange, only the magnitude. The sensitivity of combination of changes in temperature, precipitation and doubled CO_2 concentration is very different than the sensitivity to each variable on its own.

5.2 Model structure

The land surface climate component, *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 (Fig. 5.1). Then, the C cycling component, *i.e.* MWM, 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. We referred this coupled model as CLASS3W-MWM. At the present time, the coupling is a one-way.

CLASS3W-MWM solves total runoff, including surface overland runoff, subsurface and peatland lateral flow and groundwater seepage, latent, sensible and ground heat flux, temperature and water content for 3 soil layers, water table depth, carbon storage in leaves, stems and roots, 1 soil C pool and 1 fresh litter C pool that decomposes much faster than soil C pool. The inputs required are: incoming shortwave and longwave radiation, precipitation (P), air temperature (Ta), specific humidity, wind speed, atmospheric pressure and atmospheric CO_2 concentration. The current C outputs for C fluxes are GPP and autotrophic respiration (AR) for each plant functional type, and oxic and anoxic decomposition. The detailed model description can be found in Verseghy (1991), Verseghy *et al.* (1993) and Letts *et al.* (2000) for the land surface model component, and St-Hilaire *et al.* (2008) and Chapter 3 for the C cycling model component.

Fig. 5.1: The basic coupling structure of the coupled land surface climate model (CLASS3W) and peatland C model (MWM) (referred as CLASS3W-MWM).



In CLASS3W-MWM, the soil hydrology was outlined in Verseghy (1991). Parameterization of hydraulic properties for peatland soil (or organic soil) was introduced by Letts *et al.* (2000). A water content form of Richard equation (Jury and Horton, 2004), is solved using classic soil-water characteristics curves, and unsaturated hydraulic conductivity is a function of soil water content (Campbell, 1974). A simple hydrological scheme was added to convert the distribution of soil moisture to a water table depth (WTD) based on the saturated soil volume and specific yield and retention (Letts *et al.*, 2000). These modifications worked well for fens (Comer *et al.*, 2000; Letts *et al.*, 2000), but for bogs a lateral outflow was added to update the soil water dynamics in order to simulate the water table depth properly (Ouyang *et al.*, in press).

In CLASS3W-MWM, there are 4 plant functional types (PFT) - trees, shrubs, sedges, and mosses, to represent the vegetation communities in northern peatlands. The details of the carbon model, MWM, are provided in St-Hilaire *et al.* (2008) and Chapter 3. In summary, carbon enters peatland ecosystem through photosynthesis by vascular plants, mosses and trees, if trees are present. Carbon is lost from this system through autotrophic respiration (AR) of plants, decomposition of fresh litter, and soil decomposition, *i.e.* heterotrophic respiration (HR). Photosynthesis in vascular plants is simulated for each PFT by a Farquhar biochemical approach (Farquhar *et al.*, 1980; Farquhar and von Caemmerer, 1982), coupled with canopy-level stomata conductance (Jarvis, 1976; Ball *et al.*, 1987) to solve an unconstrained PFT-specific GPP(Arora and Boer, 2003; St-Hilaire *et al.*, 2008). For non-vascular plant, *i.e.* mosses, a semi-empirical function including the effect of moss water content on photosynthetic capacity (Tenhunen *et al.*, 1976) and on total conductance of CO_2 (Williams and Flanagan, 1998) is used to replace the stomatal conductance. For a fen peatland, this unconstrained GPP is constrained by a non-linear function of WTD to compute the actual GPP rate (Chapter 3). The fixed carbon is allocated to leaves, stems and roots, following Frolking, *et al* (2002). A simple degree day approach is used for the vegetation phenology (Frolking *et al.*, 2002; St-Hilaire *et al.*, 2008). AR is composed of maintenance and growth respiration. HR is the sum of fresh litter decomposition and peat soil decomposition. Peat soil decomposition is calculated based on 2 soil carbon compartments, *i.e.* oxic C storage above WTD and anoxic C storage below WTD. For a bog peatland, the oxic and anoxic zone is subdivided by an effective WTD based on the actual WTD (St-Hilaire *et al.*, 2008), while for a fen because the roots of sedge penetrate below the WTD the effective WTD is calculated from a non-linear function of sedge net primary production (NPP) (Chapter 3).

5.3 Evaluation study sites and data sets

5.3.1 Evaluation study sites

The evaluation peatlands are Mer Bleue (MB), an ombrotrophic bog, and Degero Stormyr (DS), a minerotrophic poor fen. There has been continuous measurement of carbon, water and energy exchange between peatland surface and the atmosphere since May 1998 at MB (Lafleur *et al.*, 2003; Roulet *et al.*, 2007) and since 2001 at DS (Sagerfors, 2007; Sagerfors *et al.*, 2008).

5.3.1.1 Mer Bleue bog

Mer Bleue, located 10 km east of Ottawa, Ontario, Canada (45.41° N, 75.48° W, 69 m a.m.s.l), in a postglacial channel, began to accumulate organic matter in 9000 a B.P. and switched to a bog phase between 7100-6800 years ago (Auer, 1930; Mott and Camfield, 1969). The climate of the region is classified as cool continental temperate, with a 30-year (1971-2000) mean annual temperature of 6.0 ℃ and a total annual precipitation of 943 mm, 235 of which falls as snow between December and March (http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html) (Table 5.1). Total precipitation is relatively evenly distributed among the 12 months, with a minimum of 60 mm in February and a maximum of 90 mm in July. The warmest month is July and the coldest in January with 30-year average monthly temperatures of 20.9 ℃ and -10.8 ℃ respectively. The mean monthly temperature is > 0 ℃ from April to October and > 10℃ from May to September. The 1971-2000 average number of days with minimum temperature > 0 ℃ is 206 days.

MB is a 28 km^2 ombrotrophic bog (Moore *et al.*, 2002; Lafleur *et al.*, 2003; Roulet *et al.*, 2007) (Table 5.1). The measurement site is located in the northern most arm of MB. It is a slightly domed bog with a peat depth of 5-6m in the centre. The dominant evergreen (*Chamaedaphne calyculata,Ledum groenlandicum, Kalmia angustifolia*), and deciduous (*Vaccinium myrtilloides*) shrubs have an average height of 20-30 cm and leaf area index (LAI) of ~1.3

(one-sided) (Moore *et al.*, 2002; Bubier *et al.*, 2006). Sedges (*Eriophorum vaginatum*) comprise a sparse cover and a few small trees (*Picea mariana, Larix laricina, Betula populifolia*) are present on hummocks. The grounds are covered by *Sphagnum* mosses (*S. capillifolium, S. magellanicum, S. Fuscum*). However, the peatland area in this study, where the eddy covariance tower and other measurement instruments for the surface and soil climate are set up, is only covered by mosses and shrubs. Total aboveground biomass for vascular species, measured in 1999 and 2004, averaged 356 ± 100 g m^{-2} (Moore *et al.*, 2002) and 433 g m^{-2} (Bubier *et al.*, 2006) respectively, and total belowground biomass, measured in 1999, was 1820 ± 660 g m^{-2}. *Sphagnum* capitulum biomass was 144 ± 30 g m^{-2} in 1999 (Moore *et al.*, 2002) and 158 g m^{-2} in 2004 (Bubier *et al.*, 2006). More details about the vegetation communities and their characteristics can be found in Moore *et al.* (2002) and Bubier *et al.* (2006).

5.3.1.2 Degero Stormyr fen

Degerö Stormyr (DS) , located in Northern Sweden (64°11’N, 19°33’E), is an acid, oligotrophic, minerogenic, mixed mire system covering 6.5 km^2 (Sagerfors, 2007; Sagerfors *et al.*, 2008) (Table 5.1). The mire consists of interconnected smaller mires divided by islets and ridges of glacial till and is situated between two rivers. The depth of the peat is generally between 3-4 m, but depths up to 8 m have been observed. The deepest peat corresponds to an age of ~8000 years. The climate of the region, defined as cold temperate humid, has a 30-year average annual precipitation and temperature of 523 mm and 1.2 ℃

respectively, and average monthly temperatures in July and January of 14.7 ℃ and -12.4 ℃ (Alexandersson *et al.*, 1991; Sagerfors, 2007; Sagerfors *et al.*, 2008) (Table 5.1). Daily mean temperature is > 5 ℃ (Moren and Perttu, 1994) for ~153 days for the study period of 2001 to 2006 (Sagerfors, 2007; Sagerfors *et al.*, 2008).

The vascular plant community is dominated by *Eriophorum vaginatum* L., *Vaccinium oxycoccos* L., *Andromeda polifolia* L.,*Rubus chamaemorus* L. with both *Carex limosa* L. and *Schezeria palustris* L. occurring more sparsely. *Carex rostrata* L. is found within the margins of this fen, where there is a direct minerogenic water inflow. The surface vegetation in the wet carpets is dominated by *Sphagnum majus* Russ. C. Jens, and the lawns by *S. balticum* Russ. C. Jens. and *S. lindbergii* Schimp, while *S. fuscum* Schimp. Klinggr. and *S. rubellum* Wils. are dominant on the hummocks.

Table 5.1: The detailed physical characteristics and mean climate condition for the two evaluation peatlands.

Note: MB: Mer Bleue; DS: Degero Stormyr; Ta: Air temperature; P: Precipitation.

Characterstics	**Bog (MB)**	**Fen (DS)**
Name	Mer Bleue	Degero Stormyr
Location	45.41°N, 75.48°W, Eastern Canada	64°11’N, 19°33’E, Northern Sweden
Climate	Cool continental temperate	Cold temperate humid
Peatland classification	Ombrotrophic bog	Minerotrophic poor fen
Nutrients	Poor	Rich
Water sources	Precipitation	Precipitation, surface runoff and groundwater
Size	28 km^2	6.5 km^2
Depth of peat	5-6 m	3-4 m
Basal age	~9000 yrs	~8000 yrs
Dominant plants	Moss and Shrubs	Moss and Sedges
Surface topography	69 m a.m.s.l	270 m a.m.s.l
Mean annual Ta (℃)	6.0	1.2
Monthly max. Ta (℃)	20.9	14.7
Monthly min. Ta (℃)	-10.8	-12.4
Days above 0 ℃	206.0	150.0
Mean annual P (mm)	943.0	523.0
Precipitation as snow (mm)	235.0	233.0
Monthly max. P (mm)	90.0	65.0
Monthly min. P (mm)	60.0	25.0

Table 5.2: Parameters and initial values used in CLASS3W-MWM for MB and DS.

Parameter	**Bog(MB)**	**Fen(DS)**	**Units**	**Description**	**Reference/Source**
Values for Model Parameters at 25°C					
J_{max}:V_{max}	1.67	1.67	-	ratio	(Medlyn *et al.*, 2002)
Mosses					
V_{cmax25}	6	6.5	μ mol $m^{-2}s^{-1}$	max carboxylation rate (spring)	
	14	14	μ mol $m^{-2}s^{-1}$	max carboxylation rate (summer)	
	7	7.5	μ mol $m^{-2}s^{-1}$	max carboxylation rate (autumn)	
R_{d25}	0.946	0.946	μ mol $m^{-2}s^{-1}$	dark respiration rate	(Harley *et al.*, 1986)
Shrubs/Sedges					
V_{cmax25}	17	20	μmol $m^{-2}s^{-1}$	max carboxylation rate	
Initial site specific parameters					
frac	48.7	48.7	%	biomass to carbon ratio	
B_{moss}	140	150	g biomass m^{-2}	moss capitula biomass	
$B_{min\ foliar}$	175	90	g biomass m^{-2}	min shrub/sedge foliar biomass	
$B_{max\ foliar}$	350	180	g biomass m^{-2}	max shrub/sedge foliar biomass	
LAI_moss	1.35	1.05	m^2/m^2	initial moss leaf area idex	
LAI_shrub/Sedge	0.9	0.5	m^2/m^2	initial shrub/sedge leaf area index	
Root_shrub/sedge	500	450	g biomass m^{-2}	Initial shrub/sedge root biomass	
Litter_shrub/sedge	150	250	g biomass m^{-2}	Initial shrub/sedge litter biomass	
B_{stem}	0.003		$m^3\ m^{-2}$	shrub sapwood volume	
PD_0	6	4	m	initial peat depth	
k_o	0.05/0.2	0.05/0.2	y^{-1}	initial decomposition rate for moss/shrub(sedge)	(Frolking *et al.*, 2001)

Initial values for organic soil					
Z	0.20/0.75/6.0	0.20/0.75/4.0	m	Depth to bottom of 3 soil layers	(Ouyang *et al.*, in press)
θp	0.93/0.88/0.83	0.93/0.88/0.83		Porosity for 3 soil layers	(Letts *et al.*, 2000)
θr	0.175/0.530/0.705	0.175/0.530/0.705		Specific retention for 3 soil layers	(Letts *et al.*, 2000)
θm	0.04/0.15/0.22	0.04/0.15/0.22		Residual soil water content for 3 soil layers	(Letts *et al.*, 2000)
b	2.7/6.1/9.5	2.7/6.1/9.5		Soil texture parameter	(Letts *et al.*, 2000)
Ψs	9.6E-3/9.06E-3/8.3E-3	9.6E-3/9.06E-3/8.3E-3	m	Soil matric potential at saturation	(Ouyang *et al.*, in press)
γ	1.7E-4/2.0E-6/1.0E-8	1.7E-4/2.0E-6/1.0E-8	m s^{-1}	Hydraulic conductivity at saturation	(Ouyang *et al.*, in press)

5.3.2 Data processing for the CLASS3W-MWM drivers

At both MB and DS along with the eddy-covariance measurement of CO_2 fluxes, a variety of additional environmental variables were measured that are used as inputs for CLASS3W-MWM (Lafleur *et al.*, 2003; Roulet *et al.*, 2007; Sagerfors *et al.*, 2008). These are: incoming short-wave and long-wave radiation, air temperature (Ta), peatland surface temperature, precipitation, wind speed, specific humidity, atmospheric pressure and atmospheric CO_2 concentration. We used the gap-filled field measurements from MB for 1999-2006 and DS for 2001-2006 as the input drivers to CLASS3W-MWM. CLASS3W-MWM was configured and initialized for MB and DS respectively (Table 5.2). To fully represent the site-specific biogeochemical processes, several site-specific parameters are required: peat depth, foliar biomass for mosses, sedges and shrubs, vegetation root biomass, V_{cmax25} (the maximum velocity of Rubisco carboxylation at 25 ℃) for mosses, sedges and shrubs (Table 5.2). In addition to these site-specific parameters, a complementary data set containing model parameters based on studies reported in the literature serves for all sites within a range of general northern peatlands (see Table 1 in St-Hilaire *et al.*, 2008). Due to power outage, instrument failure and other conditions that did not satisfy the requirements of measurement, gaps exist in the measurement data. Gaps for the half-hourly measurement of environmental drivers were simply filled by their previous 5 hours' average value.

5.3.3 Data processing for tower measurement of CO_2 fluxes

In this study, an eddy-covariance (EC) tower measurement of NEE and the derivative of GPP, TER were used to represent the spatial average C fluxes at the ecosystem level for MB (Lafleur *et al.*, 2003; Roulet *et al.*, 2007), but only NEE was used for DS (Sagerfors *et al.*, 2008). The fluxnet-Canada measurement and processing protocols were used in our flux data processing for MB (Protocols for EC Flux Measurement Protocols, August 2003: http://www.fluxnet-canada.ca/). The measurement and EC flux data processing details for DS can be found in Sagerfors, *et al* (2008).

5.3.4 Model spin-up

The peat decomposition model (PDM) (Frolking *et al.*, 2001) was used to initialize a "representative" vertical profile of mass loss rates for bogs and fens respectively for CLASS3W-MWM (St-Hilaire *et al.*, 2008). The vertical profile was developed using a long-term constant water table depth of a representative bog and fen, but a modifier representing the effect of anoxic condition on decomposition was applied in PDM (St-Hilaire *et al.*, 2008). In CLASS3W-MWM, a different modifier, *i.e.* 0.1 and 0.025, was used for a bog and fen respectively. Then for CLASS3W-MWM the effective oxic and anoxic decomposition rates for a bog and fen were derived by integrating the decomposition curve of the vertical profile in oxic and anoxic zone respectively in PDM. The effective oxic and anoxic decomposition rates for a bog and fen were kept as constant to compute the oxic and anoxic decomposition for MB and DS respectively for the whole simulation period.

5.4 Evaluation procedures

We evaluated the performance of CLASS3W-MWM by starting with a model stability test for the MB site. We did an 80 year simulation by repeating 10 times the 1999-2006 dataset. The simulated key variables, such as WTD and soil T, were also compared with the observations. We then compared the simulated CO_2 fluxes with the observed ones for MB and net ecosystem production (NEP) for DS.

CLASS3W-MWM was run with a half-hourly time step for the surface and soil climate components and an hourly time step for the C cycling components. Then the simulated hourly CO_2 fluxes were summed up to obtain the daily and annual CO_2 fluxes. CLASS3W-MWM calculates GPP and AR for mosses, sedges and shrubs separately. The PFT-specific GPP are summed to obtain the ecosystem-level GPP. NPP was computed by subtracting AR from GPP. Heterotrophic respiration (HR, composed of fresh litter decomposition, oxic decomposition [oxic HR] and anoxic decomposition [anoxic HR]) is subtracted from NPP to get NEE. All of the respiration components, including maintenance respiration, growth respiration, fresh litter decomposition, oxic and anoxic HR , are added up to give TER, *i.e.* TER=AR+HR. We use NEE to represent the net ecosystem production (NEP). We follow the convention and terminology of

Chapin III *et al* (2006), hence a positive NEP means a C uptake by the peatland and negative NEP represents a C source to the atmosphere.

The statistical indices used in this study to evaluate model performance are the root mean square error (RMSE), that combines the systematic (RMSEs) and unsystematic RMSE (RMSEu), where $RMSE^2=RMSEs^2+RMSEu^2$ (St-Hilaire *et al.*, 2008), the coefficient of determination (r^2) and Willmott's index of agreement (d*) where 0 indicates no agreement and 1 indicates perfect agreement between simulated and observed values (Willmott, 1982, 1985).

5.5 Results

5.5.1 Model stability test

To test the model's stability we ran CLASS3W-MWM for 80 years by using the 1999-2006 data for MB. WTD showed inter-annual and seasonal variation, but ranged between 10 and 65 cm (Fig. 5.2 a) with a 8 year repeated pattern, indicating that the model has no drift. The first layer of soil temperature (Soil1_T) also showed inter-annual and seasonal variation, ranging between 0 and 25 ℃ (Fig. 5.2 b) with no drift for the 80 years. We conclude from this analysis that variations in simulated outputs result from the variability in the model inputs and not the model structure.

WTD and soil temperature are the key environmental determinants for the

C cycling in northern peatlands. Hence, we compared the simulated summer WTD and first layer of soil temperature (soil1_T) with the observations for MB (Fig. 5.3 a and b) and DS (Fig. 5.3 c and d). The 1:1 scatter plots and their associated r^2 (>0.48 for WTD and >0.73 for soil1_T) showed that CLASS3W-MWM did not show a systematic overestimate or underestimate of WTD and soil1_T. This verification established a good foundation for surface and soil climate to model the CO_2 cycling for northern peatlands using CLASS3W-MWM.

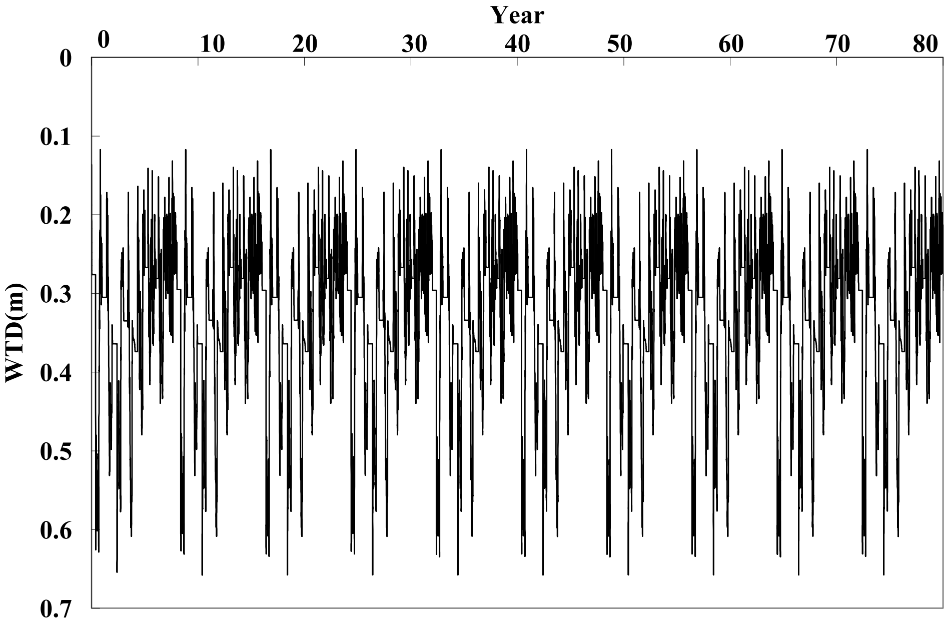
5.5.2 Comparison of annual patterns of CO_2 fluxes

5.5.2.1 Mer Bleue (MB)

CLASS3W-MWM simulated the annual GPP reasonably well (~2% difference between simulated and observed for the 8 years), but the year-by-year variation did exist, with a range of differences between -19% and +20% (Table 5.3). Simulated GPP overestimated observed GPP by 84-105 g C m^{-2} yr^{-1} in 2000-2003, while simulated GPP underestimated observed GPP by 39-144 g C m^{-2} yr^{-1} for the rest of the study period. The 2000-2003 years were the driest year of the 8 years (Fig. 5.4). Simulated annual GPP was not significantly different than observed annual GPP ($p>>0.05$). At MB, the simulation showed that shrubs contributed a higher percentage to the total GPP than mosses. Moss GPP was 39-45% of total GPP while shrub GPP contributed 55-61% of total GPP.

Fig. 5.2: 80 years simulation of (a) water table depth (WTD) and (b) the first layer's soil temperature (soil1_T) based on the 10 repeated simulation of 1999-2006 for Mer Bleue (MB).

(a) WTD



(b) soil1_T

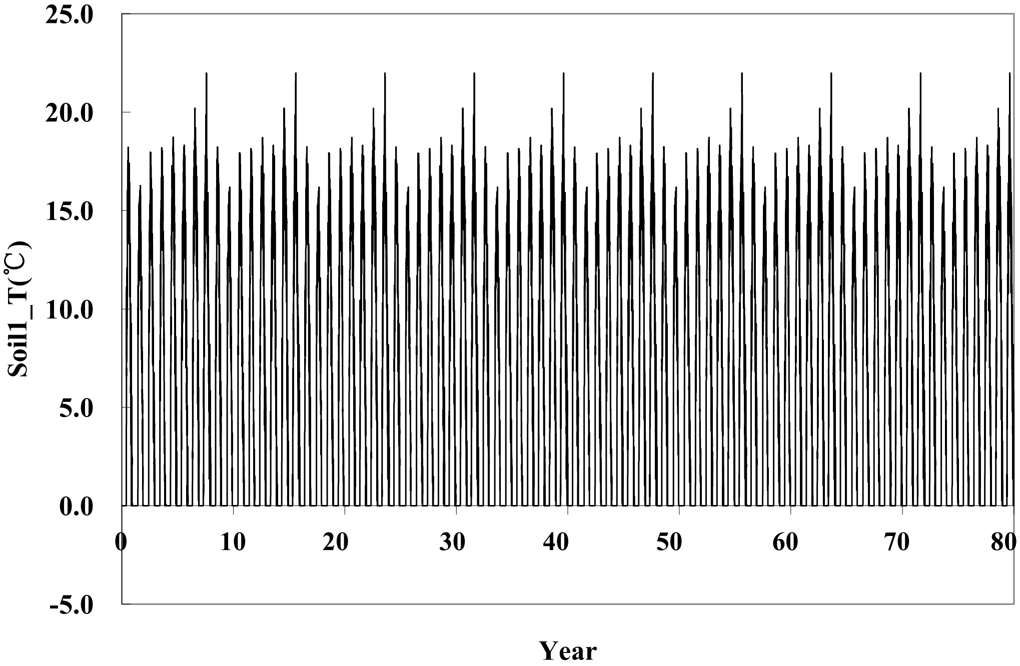
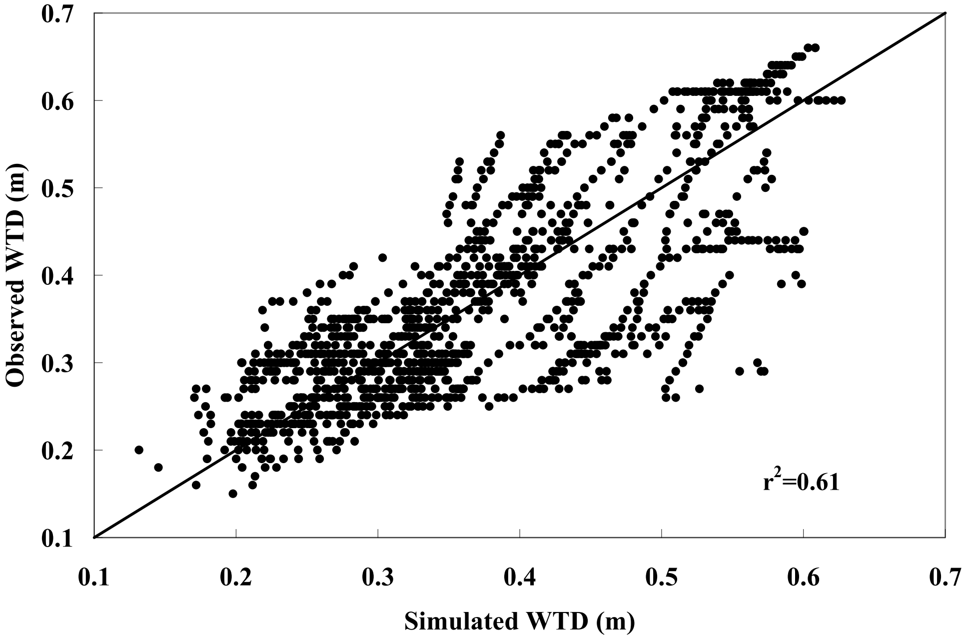
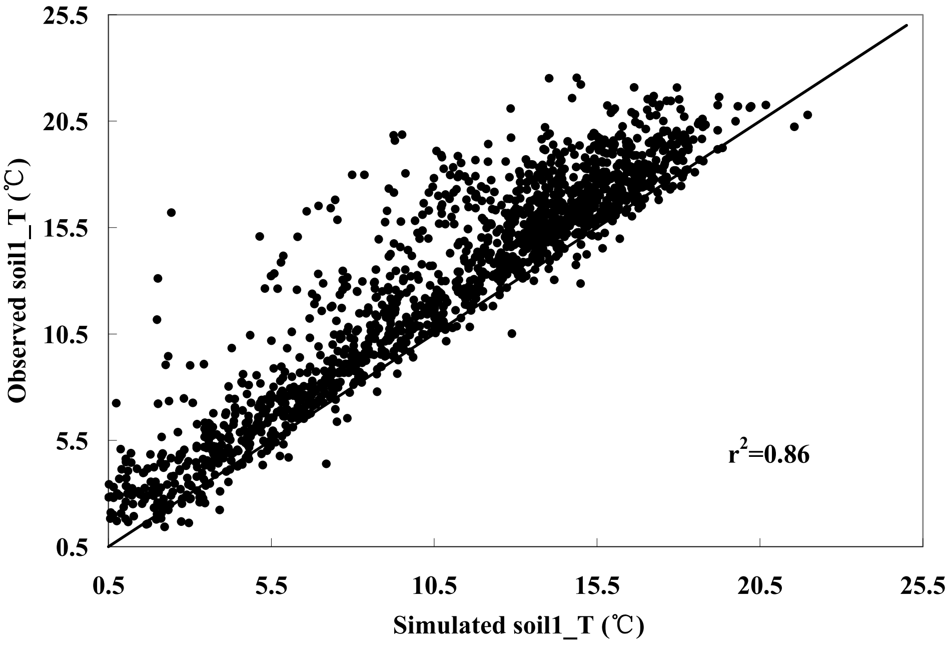


Fig. 5.3: Comparison of CLASS3W-MWM simulated summer WTD and first layer soil T (soil1_T) with observed ones for MB ((a) and (b)) and Degero Stormyr (DS) ((c) and (d)). Note: The black line in the graph is the perfect 1:1 line.

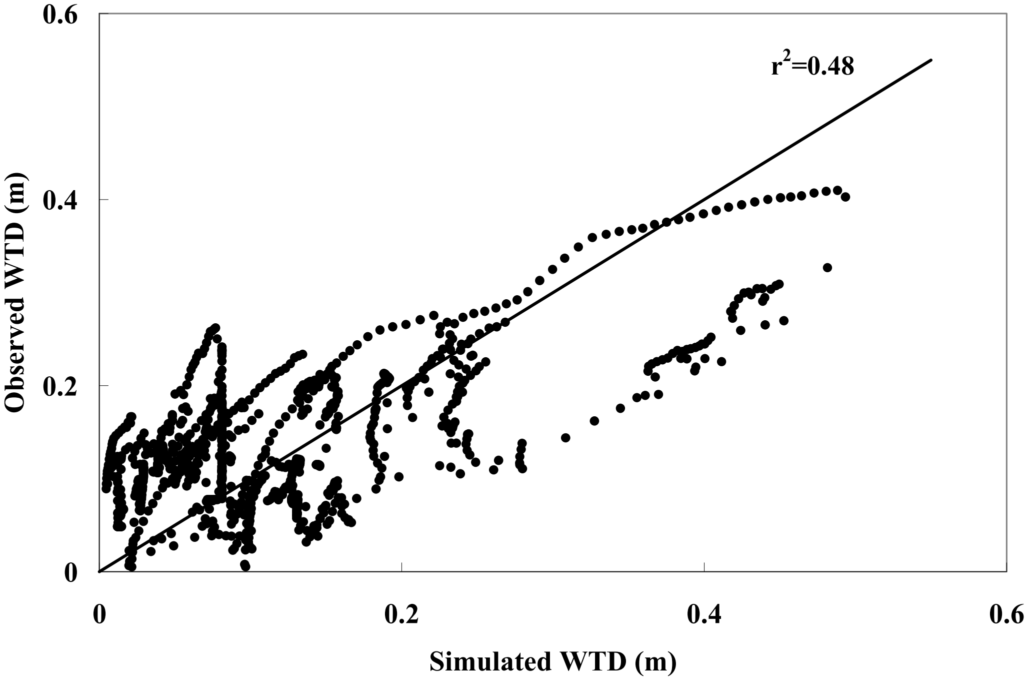
(a) Summer WTD for MB



(b) Summer soil1_T for MB



(c) Summer WTD for DS



(d) Summer soil1_T for DS

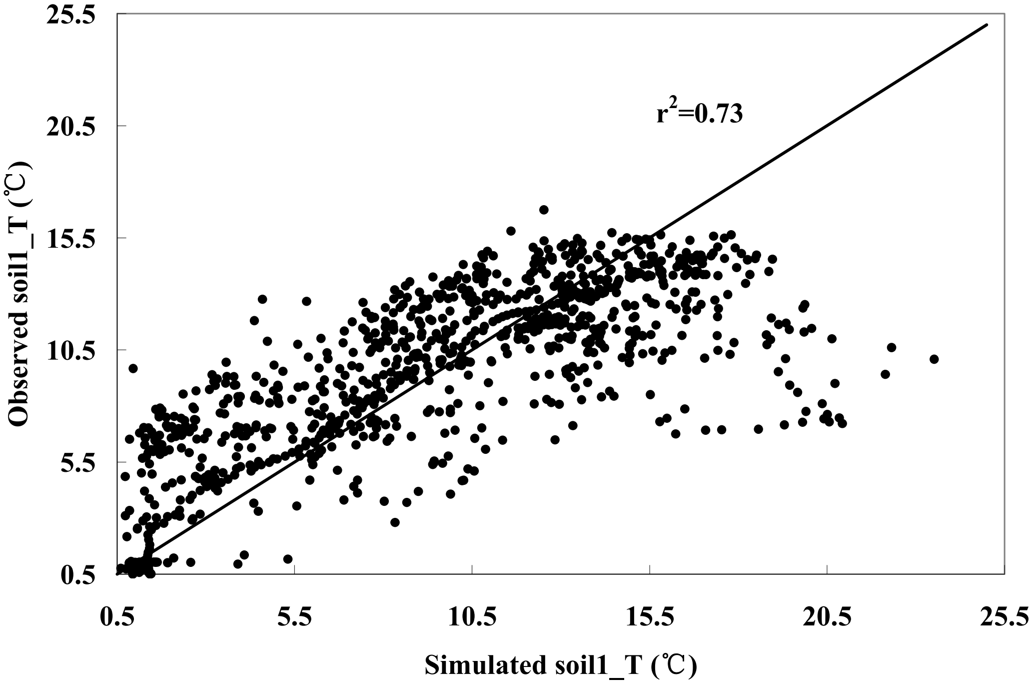
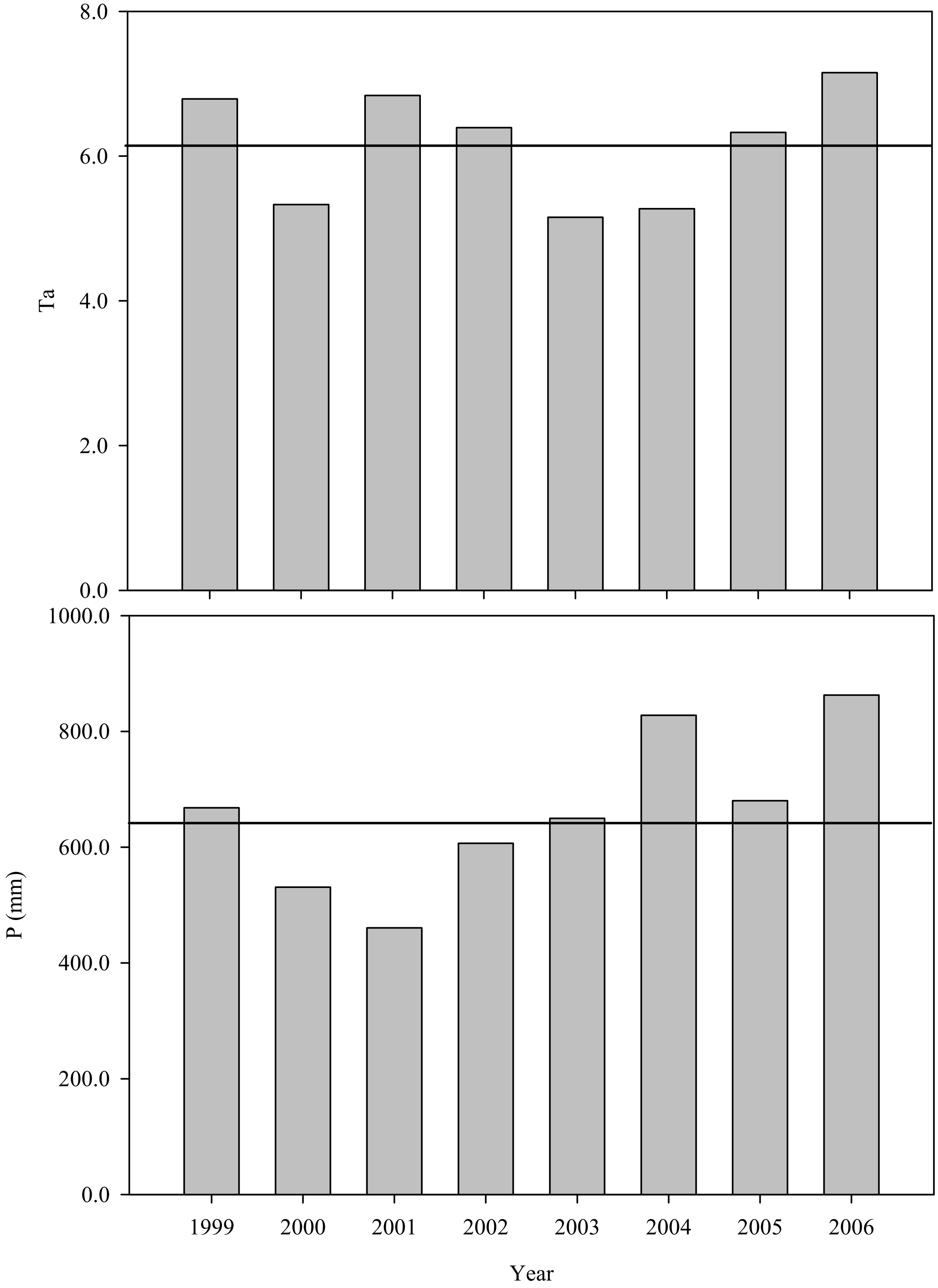


Fig. 5.4: Annual average air temperature (Ta:℃) and precipitation (P:mm) for 1999-2006 for MB.

Note: The black solid line represents the 8 years' average value.



CLASS3W-MWM simulated annual TER better than GPP (~5% difference for the 8 years) with a range of 5-10% difference, with the exception of 1999 where the difference was ~20% (Table 5.3). CLASS3W-MWM underestimated TER in 5 of the 8 years and the three years with overestimations occurred in drier than the normal years (Fig. 5.4). Simulated AR represents ~70-77% of TER with an average of 73% while HR was ~23-30%. Moss AR represented ~ 24-28% and shrub AR ~ 43-49% of TER. The relative contribution of mosses and shrubs AR to TER varied little from year-to-year. Oxic decomposition contributed 8 times more to TER than did anoxic decomposition.

The difference between the two relatively large numbers, GPP-TER, gives NEP. Observed NEP represents between 0.009 and 0.20 of GPP or TER and the discrepancy between the observed and simulated NEP is within the uncertainty of either GPP or TER (Table 5.3). Over the 8 years the difference is ~38 g C m^{-2} yr^{-1}, which is within the standard deviation of the measurements reported in Roulet *et al*. (2007). In the first five years NEP was overestimated and in the last three years it was underestimated.

The year-to-year variation of simulated NPP (Table 5.3) falls within the range that Moore *et al.* (2002) reported for a bog, for shrub above-ground NPP: 21-169 g C m^{-2} yr^{-1}; for moss NPP: 8-190 g C m^{-2} yr^{-1}; and total NPP (assuming biomass is 50% C): 79-377 g C m^{-2} yr^{-1} . Moore *et al.* (2002) estimated at MB above-ground shrub and moss NPP to be 80 and 85 g C m^{-2} yr^{-1} respectively in 1999, while CLSS3W-MWM simulated 121 and 141 g C m^{-2} yr^{-1} for the same year 1999 (Table 5.3).

Fig. 5.5: Annual average air temperature (Ta:℃) and precipitation (P:mm) for 1999-2006 for DS.

Note: The black solid line represents the 8 years' average value.

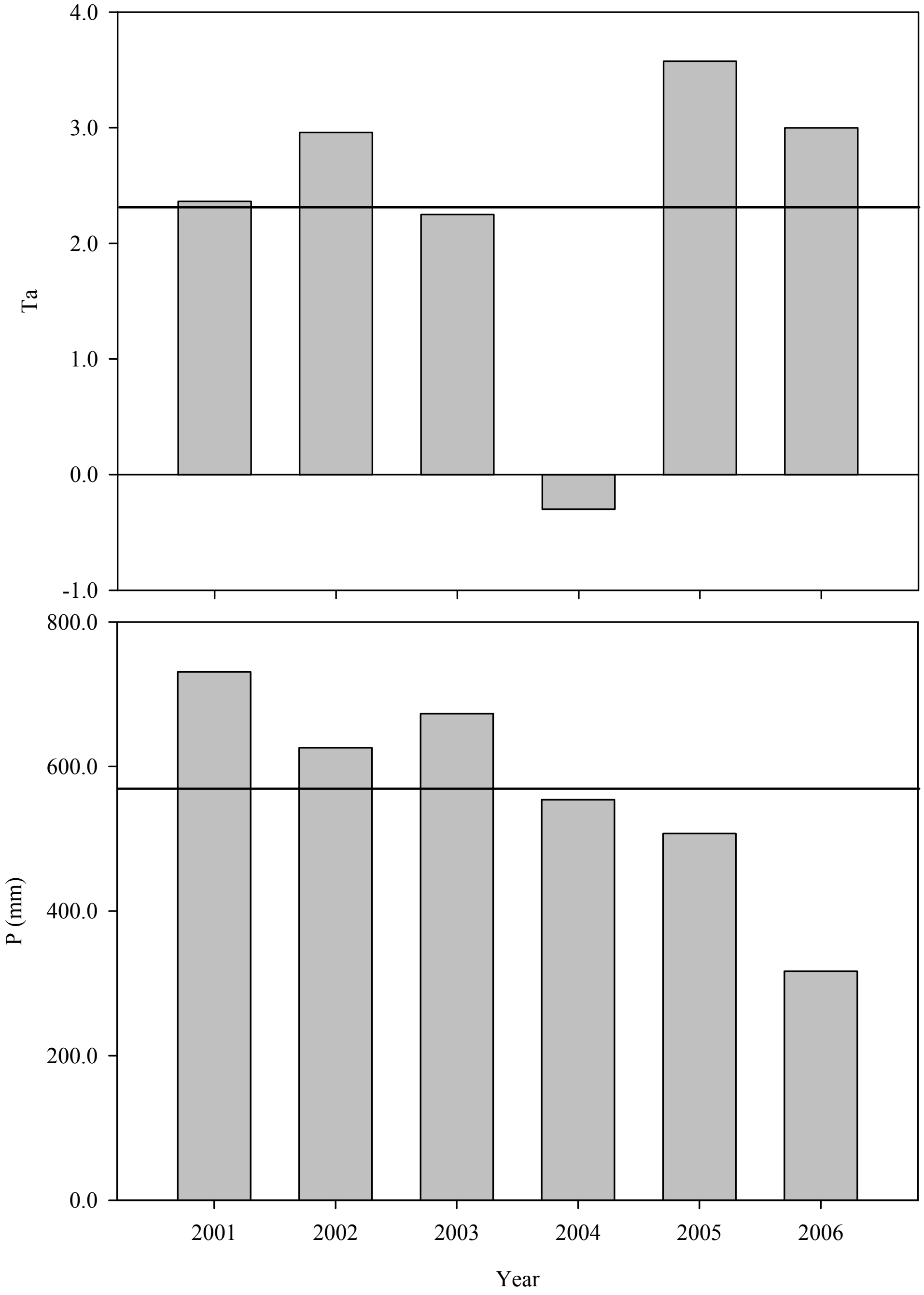


Table 5.3: CLASS3W-MWM simulated and observed annual GPP (GPP_M,GPP_O), TER (TER_M,TER_O), NEP (NEP_M,NEP_O) for MB; the difference between the simulated and observed fluxes (Diff); and the annual NPP and the percentage contribution of each simulated component. The suffix “O” represents observed fluxes, while “M” for simulated fluxes. The 8 years’ average is also shown.

Note: for GPP and NEP, positive difference between simulated and observed fluxes means overestimate, while negative underestimate. But for TER, positive means underestimate (*i.e.* less negative value for TER), while negative overestimate. Unit for C fluxes is g C m^{-2} yr^{-1}.

		GPP							TER					NEP			NPP	
Year	GPP_O	GPP_M	Diff	Moss	Shrub	TER_O	TER_M	Diff	AR	MossAR	ShrubAR	HR	NEP_O	NEP_M	Diff	NPP_M	Moss	Shrub
				%	%				%	%	%	%					%	%
1999	646.2	607.0	-39.2	42.5	57.5	581.7	466.3	115.4	73.8	25.1	48.7	26.2	64.6	140.7	76.2	262.9	53.7	46.3
2000	463.2	568.7	105.5	45.1	54.9	431.3	475.9	-44.6	71.2	28.1	43.1	28.8	31.9	92.8	60.9	229.8	53.5	46.5
2001	543.3	638.5	95.2	42.5	57.5	541.3	496.4	44.8	71.4	24.0	47.3	28.6	2.0	142.1	140.0	284.2	53.4	46.6
2002	511.0	595.3	84.3	43.6	56.4	498.1	501.4	-3.3	70.1	25.9	44.2	29.9	12.9	93.9	81.0	244.0	53.1	46.9
2003	494.6	592.2	97.6	40.8	59.2	480.2	521.9	-41.6	73.3	26.9	46.3	26.7	14.4	70.4	56.0	209.9	48.2	51.8
2004	683.0	619.3	-63.7	41.2	58.8	567.8	517.9	49.9	75.5	28.3	47.1	24.5	115.2	101.4	-13.7	228.5	47.5	52.5
2005	688.3	632.3	-55.9	38.7	61.3	597.9	566.1	31.8	75.9	27.6	48.3	24.1	90.4	66.2	-24.1	202.7	43.6	56.4
2006	772.2	628.2	-144.0	39.8	60.2	624.7	556.8	67.9	76.9	28.8	48.0	23.1	147.5	71.4	-76.1	200.2	44.8	55.2
Ave	600.2	610.2	10.0	41.8	58.2	540.4	512.8	27.5	73.5	26.9	46.6	26.5	59.9	97.4	37.5	232.8	49.7	50.3

Table 5.4: CLASS3W-MWM simulated GPP (GPP_M), TER (TER_M), NEP (NEP_M), NPP (NPP_M) and observed NEP (NEP_O), the difference between the simulated and observed NEP (Diff), and the percentage contribution of each simulated component for DS. The suffix “O” represents observed fluxes, while “M” for simulated fluxes. The 6 years’ average is also shown.

		GPP				TER				NEP			NPP	
Year	GPP_M	Moss	Sedge	TER_M	AR	MossAR	SedgeAR	HR	NEP_O	NEP_M	Diff	NPP_M	Moss	Sedge
	gCm^{-2}yr^{-1}	%	%	gCm^{-2}yr^{-1}	%	%	%	%	gCm^{-2}yr^{-1}	gCm^{-2}yr^{-1}			%	%
2001	443.2	36.8	63.2	357.6	73.2	18.6	54.6	26.8	47.9	85.6	37.7	181.4	53.1	46.9
2002	494.8	29.9	70.1	467.5	68.5	17.5	51.0	31.5	60.6	27.3	-33.3	174.4	37.9	62.1
2003	370.6	35.1	64.9	260.6	81.9	28.9	53.0	18.1	59.1	110.0	50.9	157.1	34.8	65.2
2004	245.1	35.9	64.1	236.8	78.8	20.5	58.3	21.2	54.9	8.3	-46.6	58.4	67.6	32.4
2005	490.5	29.9	70.1	458.0	71.2	18.0	53.2	28.8	47.5	32.5	-15.1	164.2	39.1	60.9
2006	381.9	35.3	64.7	354.7	63.7	15.9	47.8	36.3	17.3	27.2	9.9	155.9	50.4	49.6
Ave.	404.3	33.8	66.2	355.9	72.9	19.9	53.0	27.1	47.9	48.5	0.6	148.6	47.2	52.8

5.5.2.2 Degero Stormyr (DS)

Over the 6 years of the study the mean observed and simulated NEP were almost identical though the simulated NEP had a much larger year-to-year variation (Table 5.4). The year-to-year difference between observed and simulated NEP was in the same order of the magnitude as NEP, but < NEP. NEP was overestimated and underestimated equally. But the underestimate mainly occurred in drier than normal years (Fig. 5.5). As with MB, the simulated NEP for DS was within the standard deviation of the observation (Sagerfors, 2007; Sagerfors *et al.*, 2008).

We have not derived GPP and TER from the observed NEP yet. Our simulation showed that NEP was a small proportion of GPP (Table 5.4). Moss GPP contributed 30-37% to simulated GPP and sedge contributed the rest. As in MB there was little year-to-year variation in the proportion of moss to sedge GPP. Simulated AR contributed 63-82% of simulated TER and HR contributed the rest. Simulated moss AR contributed 16-29% while simulated sedge AR contributed 48-58%. The range and portioning of simulated NPP (Table 5.4) fall within the range of 75-150 g C m^{-2} yr^{-1} and the equal contribution of moss and sedge reported by Nilsson and Bohlin (2001).

5.5.3 Seasonal and inter-annual variability of CO_2 fluxes

5.5.3.1 Mer Bleue (MB)

CLASS3W-MWM captured the inter-annual and seasonal variability of GPP, TER and NEP at MB well (Fig. 5.6), though it underestimated the summer peak GPP and TER. CLASS3W-MWM underestimated the peak GPP by 1-2 g C m^{-2} d^{-1}. In the summer time, maximum observed GPP ranged between 5.0 and 8.0 g C m^{-2} d^{-1}, while maximum simulated GPP ranged between 5.0 and 6.0 g C m^{-2} d^{-1}. CLASS3W-MWM underestimated the summer peak TER by about 1-2 g C m^{-2} d^{-1}. Maximum observed daily TER ranged between 4 and 7 g C m^{-2} d^{-1} in the summer, while maximum simulated daily TER ranged between 3 and 4 g C m^{-2} d^{-1}. The discrepancy between the simulated and observed NEP ranged between -1 and 1 g C m^{-2} d^{-1}, where positive means overestimation and negative indicates underestimation (Fig. 5.6). In general, maximum underestimation or overestimation occurs in the summer time when both vegetation photosynthesis and soil respiration are larger. But overall, there is no systematic and obvious overestimation or underestimation bias in terms of NEP simulation.

However, the underestimation error for the summer peak GPP and TER in the first 2 years, *i.e.* 1999 and 2000, is greater than that in the other years (Table 5.5). The NEP does not show the same pattern, probably due to the cancellation of errors in both GPP and TER. Further, we have also investigated the limits on the shrub foliar biomass that was suggested in St-Hilaire, *et al.* (2008) as a potential source of this problem. Our results showed that relaxation of the limits on the shrub foliar biomass did not improve the performance significantly (Table 5.5). Increasing shrub biomass reduces the moss GPP because more light is intercepted by shrubs and thus less light is available for moss photosynthesis.

Therefore GPP comes out to be the same even when the max shrub foliar biomass is increased by +100%.

The statistic indices indicate that CLASS3W-MWM can simulate the CO_2 exchange of a bog reasonably well (Fig. 5.7 and 5.8). The statistical performance for NEP is much lower than that for GPP and TER, but still well within the acceptable limits. In all cases the systematic components of RMSE are less than the unsystematic ones indicating that better parameters rather than changes in model structure could improve the model's performance (Comer *et al.*, 2000; Letts *et al.*, 2000).

Fig. 5.6: Temporal trend and comparison of daily observed and CLASS3W-MWM simulated GPP (top panel), TER (middle panel) and NEP (bottom panel) for 1999-2006 for MB.

Note: Filled circles are for observed CO_2 fluxes and open circles for CLASS3W-MWM simulated CO_2 fluxes.

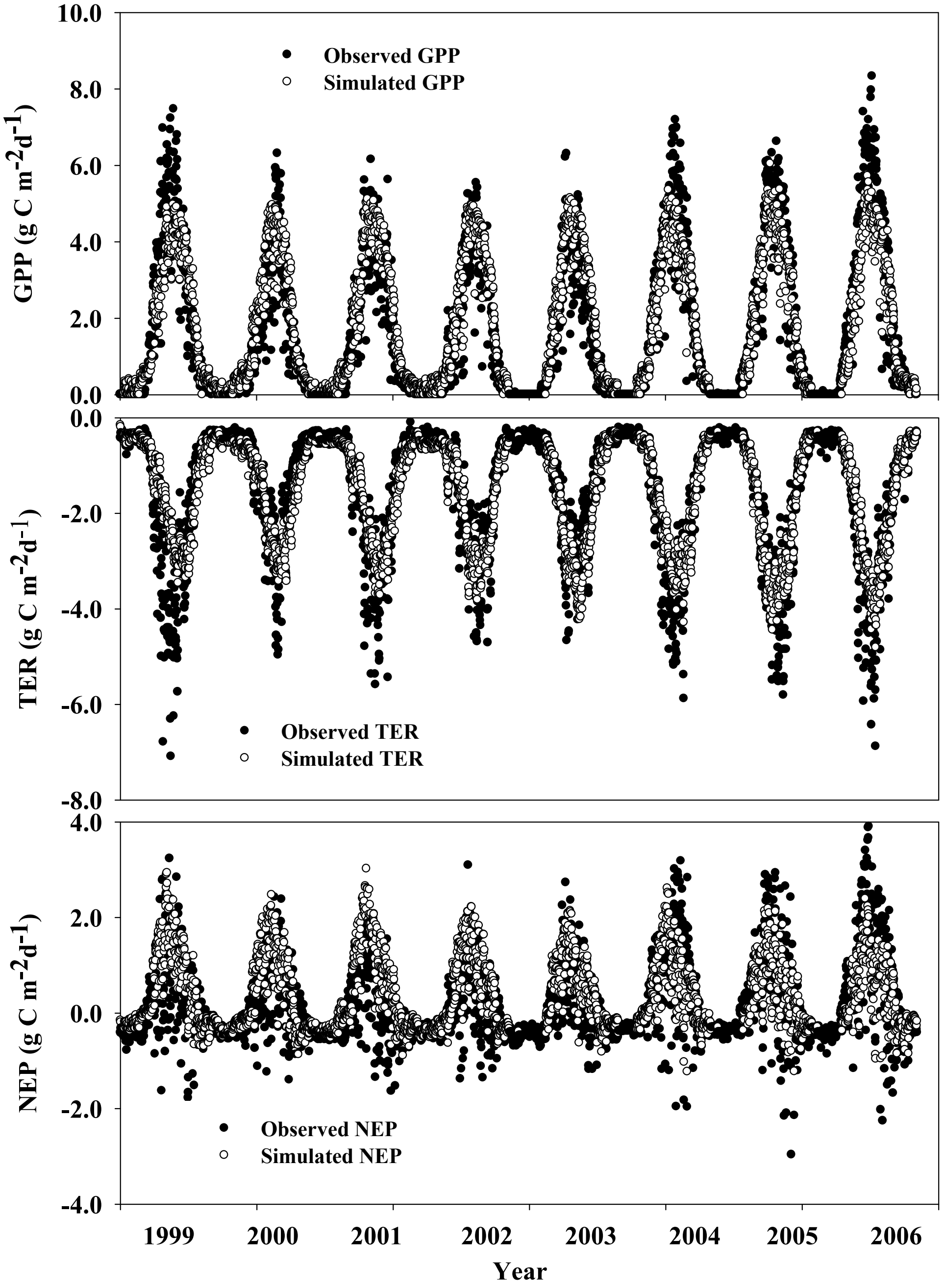


Fig. 5.7: The 1:1 scatter plots of observed and CLASS3W-MWM simulated daily GPP and TER for MB for 1999-2006. The solid black line is the perfect 1:1 line. Filled circles are for GPP and open circles for TER.

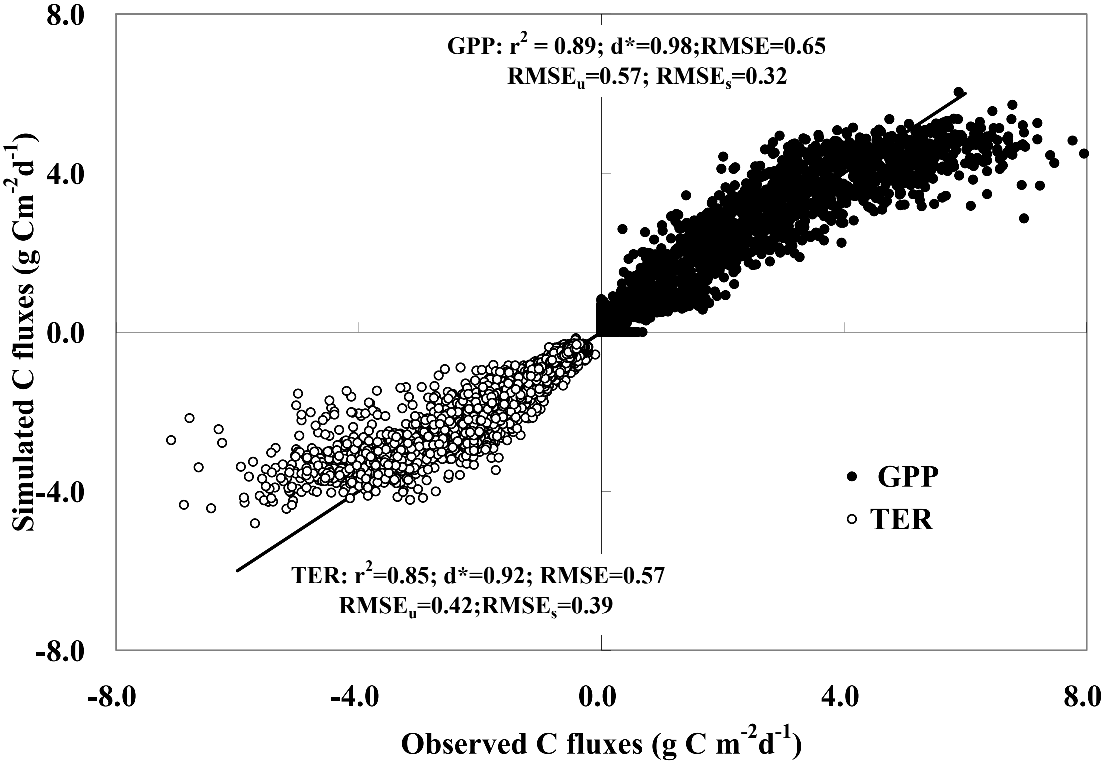


Fig. 5.8: The 1:1 scatter plots of observed and CLASS3W-MWM simulated daily NEP for MB for 1999-2006. The solid black line is the perfect 1:1 line.

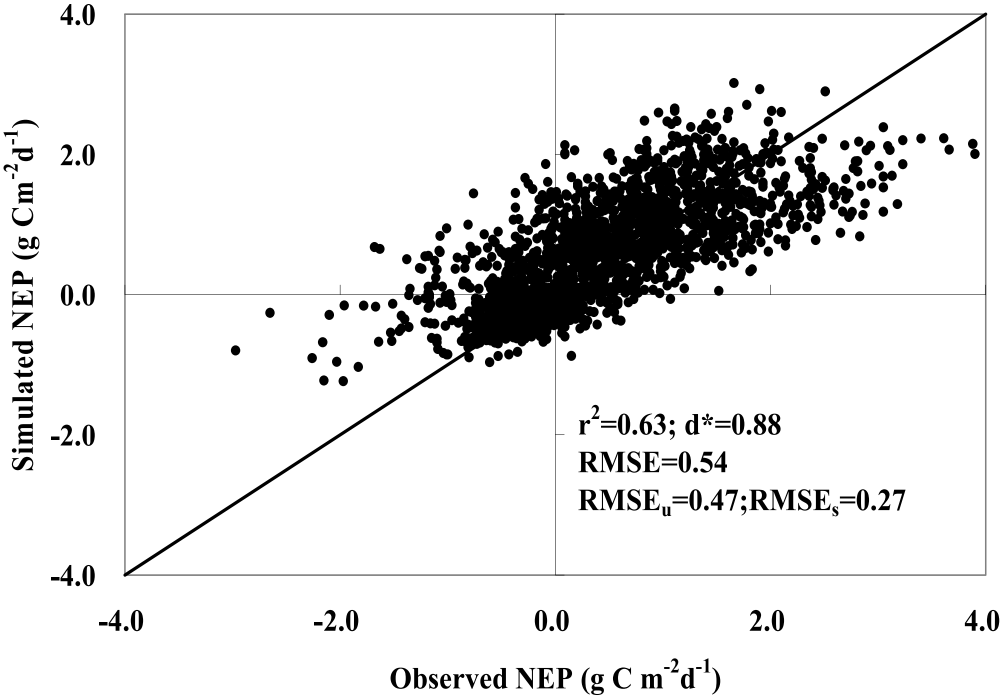


Table 5.5: The r^2 (coefficient of determination) for the 1:1 comparison between simulated and observed GPP, TER and NEP at MB for 1999-2006. The suffix 0 indicates the simulation with the original value for the maximum shrub foliar biomass and 100 with the increased maximum shrub foliar biomass by 100%.

Year	GPP0	GPP100	TER0	TER100	NEP0	NEP100
1999	0.87	0.79	0.67	0.62	0.65	0.54
2000	0.89	0.85	0.85	0.82	0.62	0.56
2001	0.91	0.87	0.86	0.84	0.64	0.49
2002	0.93	0.88	0.91	0.88	0.67	0.54
2003	0.92	0.86	0.89	0.87	0.70	0.50
2004	0.94	0.90	0.93	0.89	0.67	0.59
2005	0.96	0.94	0.93	0.92	0.78	0.66
2006	0.94	0.89	0.92	0.88	0.85	0.73

Table 5.6: Sensitivity of CLASS3W-MWM simulated GPP, AR, NPP, NEP, TER, OxicHR and AnoxicHR to changes in air temperature (Ta), precipitation (P), atmospheric CO_2 concentration [CO_2] and the combination of the individual change, expressed as a relative change in percentage to the base line fluxes, for MB (a) and DS (b).

Note: Changes in negative percentage indicate the decrease relative to the base line value, while changes in positive percentage indicate the increase. The changes in percentage is calculated by "(new value-base line)/base line ×100". The baseline C fluxes were calculated based on CLASS3W-MWM using the present-time climate inputs. Changes in Ta were imposed by its absolute changed values, while changes in precipitation were imposed by its relative changed percentage. Positive changes in Ta mean warmer temperature, while negative changes in Ta mean cooler temperature. Negative changes in precipitation mean decreased precipitation, while positive changes indicate increased precipitation. The atmospheric CO_2 concentration was doubled. Caution should be made that the changes were evenly distributed in the study period. The last 3 columns showed absolute C fluxes for GPP, TER and NEP when those changes were imposed. (See next 3 pages)

(a) For MB

			Moss			Shrub		HR			Total		Total	g Cm^{-2}yr^{-1}	
		GPP	**AR**	**NPP**	**GPP**	**AR**	**NPP**	**Oxic HR**	**Anoxic HR**	**NEP**	**TER**	**GPP**	**NEP**	**TER**	**GPP**
	Base line (gCm^{-2}yr^{-1})	***254.7***	***138.0***	***116.7***	***355.5***	***239.5***	***116.0***	***122.9***	***12.5***	***97.4***	***512.8***	***610.2***	***97.4***	***512.8***	***610.2***
	P(-30%)	-21.5	-30.6	-10.8	0.2	-1.1	2.9	11.1	12.8	-25.2	-5.8	-8.9	72.8	483.2	556.0
	P(-20%)	-7.6	-14.0	-0.04	0.1	-1.0	2.3	4.7	10.0	-4.7	-2.8	-3.1	92.8	498.3	591.1
P	**P(-10%)**	-1.4	-5.7	3.8	0.04	-0.4	0.9	2.4	6.4	1.6	-1.0	-0.5	99.0	507.9	606.9
	P(+10%)	0.03	4.7	-5.5	-0.03	0.3	-0.7	-1.9	-4.3	-4.4	0.8	-0.01	93.1	517.1	610.2
	P(+20%)	-0.3	7.8	-9.8	-0.04	0.8	-1.8	-3.2	-18.0	-7.5	1.3	-0.1	90.1	519.3	609.4
	P(+30%)	-0.5	9.9	-12.7	-0.1	1.2	-2.7	-4.0	-20.7	-10.8	1.8	-0.2	86.8	522.0	608.8
	Ta(-3)	-10.8	-16.7	-3.9	-21.3	-14.2	-35.8	-19.8	-26.1	-18.9	-16.5	-16.9	78.9	428.2	507.1
	Ta(-2)	-7.1	-9.0	-4.7	-13.9	-9.1	-24.0	-12.8	-7.1	-17.3	-9.9	-11.1	80.6	462.1	542.7
	Ta(-1)	-3.0	-2.5	-3.5	-6.7	-4.5	-11.3	-6.3	-1.4	-9.5	-4.3	-5.2	88.1	490.6	578.7
T	**Ta(+1)**	-1.6	2.8	-6.8	6.2	6.2	6.1	5.9	7.5	-9.5	5.3	2.9	88.2	539.9	628.1
	Ta(+2)	-6.5	5.7	-21.0	12.0	13.4	9.1	9.9	12.8	-28.5	10.5	4.3	69.6	566.6	636.2
	Ta(+3)	-11.2	6.0	-31.5	16.3	23.6	1.4	16.1	22.3	-59.3	17.0	4.9	39.6	600.3	639.9
	Ta(+5)	-29.0	-2.1	-60.8	22.7	40.8	-14.7	31.1	29.3	-133.4	26.7	1.1	-32.5	649.7	617.2
CO_2	**2CO_2**	15.4	0.0	33.6	37.2	21.1	70.4	35.3	0.04	79.6	18.3	28.1	174.9	606.9	781.7
T+P	**2+(+30%)**	0.5	23.6	-26.9	11.9	14.6	6.2	4.3	2.9	-30.6	14.3	7.1	67.6	586.0	653.6
	3+(+30%)	0.1	30.0	-35.4	16.2	20.8	6.8	7.5	6.2	-44.6	19.7	9.5	53.9	614.1	668.0
	5+(+30%)	-0.8	43.2	-52.9	22.5	39.7	-13.2	18.0	15.7	-103.9	34.9	12.7	-3.8	691.8	688.0
	2+(-30%)	-48.0	-46.2	-50.2	12.3	16.4	3.7	66.6	18.4	-142.2	11.7	-12.9	-41.0	572.6	531.6
	3+(-30%)	-59.5	-56.4	-63.3	17.1	23.9	3.0	79.5	20.5	-175.3	15.6	-14.9	-73.3	592.7	519.4
	5+(-30%)	-85.5	-84.9	-86.3	24.7	47.6	-22.7	289.6	-14.6	-494.2	68.5	-21.3	-383.9	863.9	480.1

T+P+CO_2	**2+(+30%)+2CO_2**	16.8	23.6	8.9	54.8	42.5	80.2	43.2	2.9	51.2	36.6	39.0	147.3	700.7	848.0
	3+(+30%)+2CO_2	16.9	30.0	1.5	61.6	54.1	77.1	49.4	6.2	30.4	45.4	43.0	127.0	745.4	872.4
	5+(+30%)+2CO_2	16.9	43.2	-14.2	72.0	77.9	59.7	61.7	15.7	-25.8	63.2	49.0	72.3	836.9	909.2
	2+(-30%)+2CO_2	-39.7	-46.2	-31.9	55.0	44.4	76.9	101.0	18.4	-76.6	33.0	15.5	22.8	682.0	704.8
	3+(-30%)+2CO_2	-52.8	-56.4	-48.5	62.1	57.2	72.2	115.5	20.5	-120.6	39.7	14.1	-20.0	716.5	696.5
	5+(-30%)+2CO_2	-83.0	-84.9	-80.7	73.2	83.5	52.1	323.7	-14.6	-441.5	93.4	8.0	-332.6	991.8	659.3

(b) For DS

			Moss			**Sedge**		**HR**			**Total**		**Total**	**g Cm^{-2}yr^{-1}**	
		GPP	**AR**	**NPP**	**GPP**	**AR**	**NPP**	**Oxic HR**	**Anoxic HR**	**NEP**	**TER**	**GPP**	**NEP**	**TER**	**GPP**
	Base line (gCm^{-2}yr^{-1})	***157.8***	***71.1***	***86.7***	***322.3***	***224.5***	***97.8***	***100.0***	***20.7***	***63.9***	***416.3***	***480.1***	***63.9***	***416.3***	***480.1***
	P(-30%)	5.8	3.3	7.9	2.1	-5.4	19.4	-4.5	-16.2	52.8	-4.3	3.3	97.6	398.5	496.1
	P(-20%)	7.2	1.5	11.9	2.9	-4.0	18.7	-6.1	-16.9	59.8	-4.2	4.3	102.0	398.8	500.8
P	**P(-10%)**	4.9	0.7	8.3	1.4	-2.1	9.4	-3.0	-9.4	33.5	-2.2	2.5	85.2	407.0	492.3
	P(+10%)	-1.4	-0.2	-2.4	-1.6	-0.8	-3.4	-1.6	-3.6	-4.8	-1.0	-1.5	60.8	412.1	472.9
	P(+20%)	-3.6	-0.04	-6.5	-3.6	-2.4	-6.3	-3.2	-5.0	-11.8	-2.3	-3.6	56.3	406.6	462.9
	P(+30%)	-3.2	-0.03	-5.8	-2.9	-2.0	-5.1	-2.8	-3.9	-10.0	-1.9	-3.0	57.5	408.2	465.7
	Ta(-3)	-7.8	-27.4	8.4	-28.6	-21.7	-44.4	-27.1	-14.3	-9.6	-23.6	-21.8	57.7	317.9	375.7
	Ta(-2)	-7.0	-18.7	2.7	-18.6	-13.9	-29.4	-15.7	-5.3	-15.3	-14.7	-14.8	54.1	355.0	409.1
	Ta(-1)	1.1	-9.6	9.9	-7.3	-4.4	-13.8	-5.4	-7.4	3.0	-5.7	-4.5	65.8	392.6	458.4
T	**Ta(+1)**	-1.5	12.6	-13.1	6.8	-1.5	25.7	9.9	-13.2	10.3	3.1	4.0	70.4	429.1	499.5
	Ta(+2)	-14.7	13.3	-37.6	-1.5	-2.9	1.5	32.3	-23.0	-91.9	7.3	-5.9	5.2	446.8	452.0
	Ta(+3)	-35.2	-5.2	-59.8	-17.5	-8.2	-38.7	48.3	-46.6	-200.9	4.0	-23.3	-64.4	432.7	368.3
	Ta(+5)	-48.1	-28.2	-64.5	-38.2	-3.9	-116.9	152.1	-61.2	-485.0	26.6	-41.4	-245.9	527.0	281.1
CO_2	**2CO_2**	12.3	0.0	22.4	23.5	11.3	51.5	37.9	-13.8	54.4	14.5	19.8	98.6	476.7	575.3

T+P	**2+(+30%)**	1.2	25.6	-18.8	14.1	6.5	31.4	21.0	-9.6	-7.3	12.5	9.8	59.2	468.1	527.3
	3+(+30%)	-15.1	17.3	-41.6	5.5	4.7	7.3	45.1	-18.8	-109.9	15.4	-1.3	-6.3	480.2	473.9
	5+(+30%)	-31.8	-1.0	-57.0	-6.4	5.3	-33.2	102.9	-40.0	-276.4	25.4	-14.7	-112.7	522.1	409.4
	2+(-30%)	-40.9	-28.9	-50.8	-25.8	-24.3	-29.3	16.0	-58.1	-120.1	-17.1	-30.8	-12.8	345.2	332.4
	3+(-30%)	-68.1	-66.6	-69.3	-44.0	-30.1	-75.9	96.8	-86.8	-333.8	-8.7	-51.9	-149.3	380.2	230.9
	5+(-30%)	-81.8	-77.6	-85.3	-42.1	-19.3	-94.4	250.6	-78.5	-627.3	32.6	-55.2	-336.8	552.1	215.3
T+P+CO_2	**2+(+30%)+2CO_2**	13.8	25.6	4.1	43.4	20.8	95.1	62.6	-24.3	61.1	29.4	33.6	102.9	538.8	641.7
	3+(+30%)+2CO_2	-4.1	17.3	-21.6	32.3	19.0	62.9	82.4	-29.5	-52.5	31.5	20.3	30.3	547.4	577.7
	5+(+30%)+2CO_2	-22.2	-1.0	-39.5	15.8	17.4	12.0	138.2	-52.6	-234.6	39.8	3.3	-86.0	581.9	495.9
	2+(-30%)+2CO_2	-33.5	-28.9	-37.3	-10.1	-17.0	6.0	36.6	-63.9	-78.0	-8.5	-17.8	14.1	380.8	394.9
	3+(-30%)+2CO_2	-64.3	-66.6	-62.3	-35.7	-25.3	-59.5	102.1	-86.7	-307.6	-4.8	-45.1	-132.6	396.2	263.6
	5+(-30%)+2CO_2	-80.0	-77.6	-81.9	-38.4	-16.9	-87.9	254.6	-80.2	-618.4	34.8	-52.1	-331.1	561.1	199.2

5.5.3.2 Degero Stormyr (DS)

For DS, we only compared CLASS3W-MWM simulated daily NEP with the observed daily NEP. The inter-annual and seasonal variability were captured reasonably well, even though variability existed year to year (Fig. 5.9 and 5.10). Maximum observed NEP ranged between 1.5 and 2.5 g C m^{-2} d^{-1} in the growing season and minimum observed NEP ranged between -1 and -1.5 g C m^{-2} d^{-1} in the non-growing season, while simulated maximum NEP ranged between 1.5 and 2.5 g C m^{-2} d^{-1} and minimum simulated NEP ranged between -1 and -1.5 g C m^{-2} d^{-1}. We did not see the truncate of peak summer NEP for the fen (Fig. 5.10). The modelled NEP occasionally exceeded the observed NEP in the summer time by 1.5 g C m^{-2} d^{-1} (Fig. 5.9), but the majority of overestimation was <1.0 g C m^{-2} d^{-1}. Underestimation also existed in the summer time, but was <0.5 g C m^{-2} d^{-1}. Modelled NEP underestimated observed NEP in the winter time with a range of <1 g C m^{-2} d^{-1}. The statistical indices indicate that CLASS3W-MWM does not have a systematic overestimation or underestimation bias for the daily NEP at DS (Fig. 5.8). As with MB, the systematic component of RMSE for NEP is much smaller than the unsystematic one.

Fig. 5.9: Temporal trend and comparison of daily observed and CLASS3W-MWM simulated NEP for 2001-2006 for DS (Filled circles are for observed NEP and open circles for CLASS3W-MWM simulated NEP).

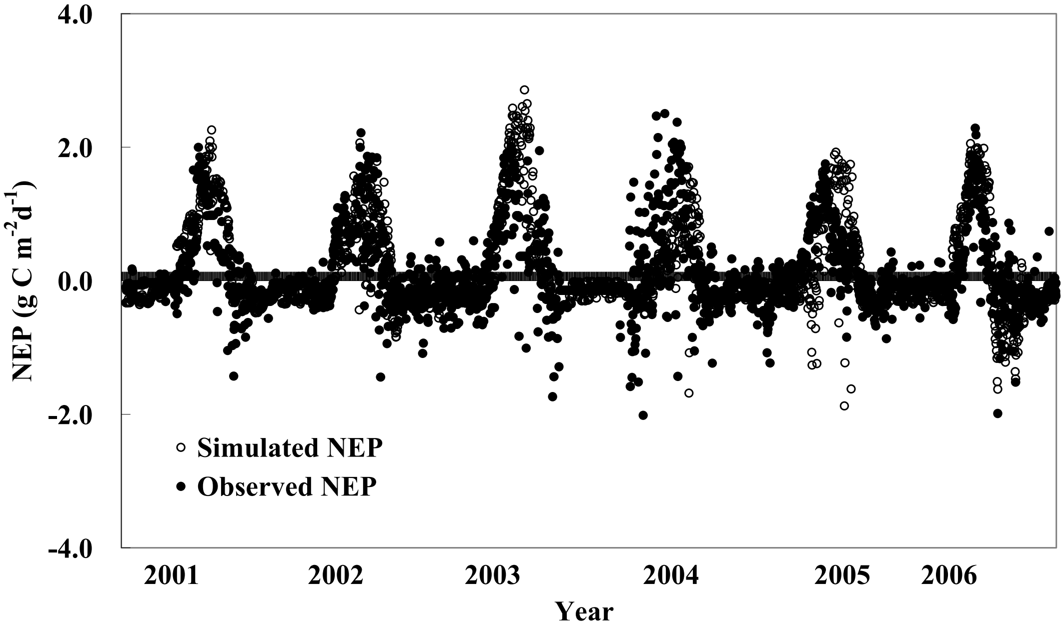
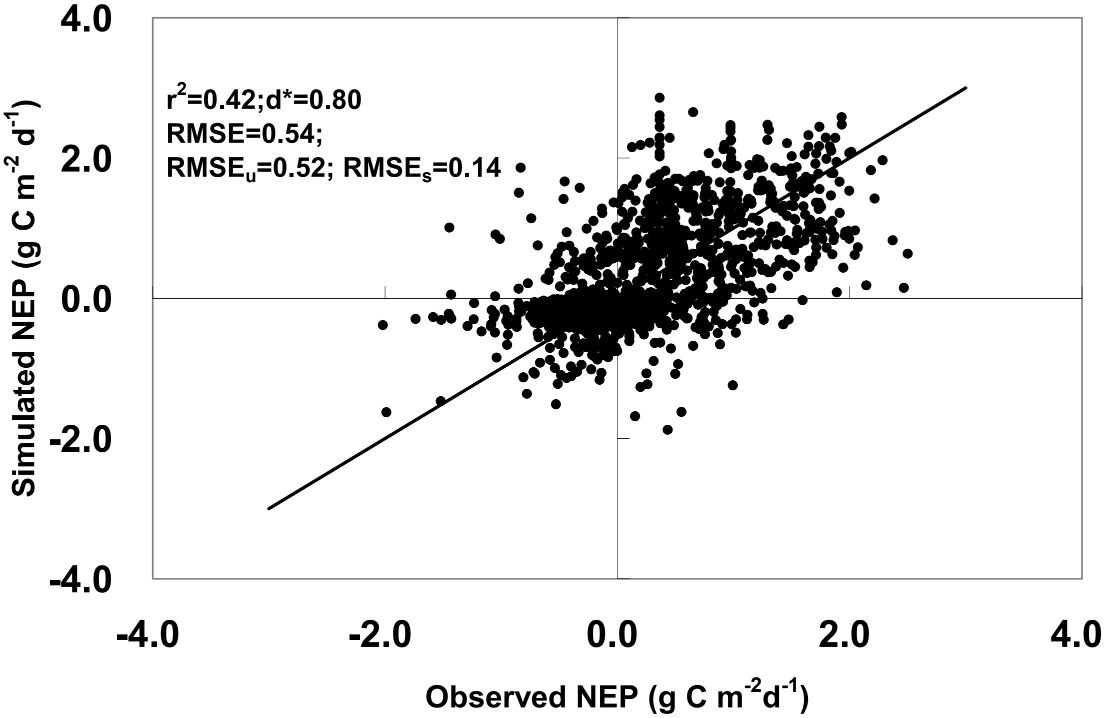


Fig. 5.10: The 1:1 scatter plots of observed and CLASS3W-MWM simulated daily NEP for DS for 2001-2006. The solid black line is the perfect 1:1 line.



5.6 Sensitivity analysis

We conducted a sensitivity analysis to examine how the C cycling in northern peatlands might change in response to possible changes in temperature, precipitation, atmospheric CO_2 concentration and some of their combination within the IPCC proposed ranges (IPCC, 2007). The sensitivity tests were done by imposing a change in air temperature (Ta) between -3 ℃ and 5 ℃ in increments of 1℃ (negative change means colder while positive warmer), a change in precipitation (P) between -30% and 30% in increments of 10% (negative change means decreased precipitation while positive increased), doubled atmospheric CO_2 concentration ($[CO_2]$) and combinations of the above: changes in Ta with a 30% increase or decrease in P (Ta+P); changes in Ta and a 30% increase or decrease in P with a doubled $[CO_2]$ ($Ta+P+CO_2$). The changes were imposed on the half-hourly Ta, P and CO_2 concentration for 1999-2006 at MB and for 2001-2006 at DS. The simulated annual mean GPP, TER and NEP were compared with the simulated baseline GPP, TER and NEP using the observation data for the study period.

5.6.1 Mer Bleue bog

Moss and shrub GPP decreases as Ta decreases, as do as AR and both oxic and anoxic HR, therefore, total GPP and TER decrease (Table 5.6 a). Since the decrease of GPP is greater than that of TER, NEP decreases slightly as Ta decreases, but remains positive, *i.e.*net C uptake. Moss GPP decreases as Ta increases, but shrub GPP increases, and since shrub GPP > moss GPP, there is a small increase in total GPP. AR and HR increase with increases in Ta. The increase of TER is greater than that of GPP, resulting in a decrease in NEP and with an increase of 5 ℃ MB becomes a source of CO_2 to the atmosphere.

But the bog appears less sensitive to changes in P than Ta. C cycling in the bog is more sensitive to decreased P than increased P (Table 5.6 a). Moss GPP increases slightly with increased P, but >20% increase in P results in a slight decrease in moss GPP. Moss GPP decreases with decreased P, as does moss AR. But the magnitude of changes in moss AR is greater than that of moss GPP, therefore moss NPP decreases with either increased or decreased P. Changes in P do not significantly influence the CO_2 cycling for shrubs. Shrub GPP increases slightly with decreased P and decreases slightly with increased P. Shrub AR increases slightly with increased P and decreases slightly with decreased P. NEP decreases with either decreased or increased P, except with 10% decrease in P. NEP drops significantly with a 30% increase or decrease in P. However, changes in P alone do not result in MB becoming a C source to the atmosphere.

CO_2 cycling at a bog is sensitive to changes in atmospheric CO_2 concentration ([CO_2]) (Table 5.6 a). Doubled [CO_2] results in a significant increase in each component of NEP, except moss AR and anoxic HR. Because of increase in total GPP > that in TER, doubled [CO_2] results in a larger C sink for MB and enhances the peat accumulation. However, some of this could result in increased dissolved organic C (DOC) export, which is not considered yet in CLASS3W-MWM.

For a combination of changes in Ta and P, we conducted a sensitivity analysis for a combination of increase in Ta and 30% increase or decrease in P (Ta+P). Changes in Ta+P result in significantly different changes in CO_2 cycling at MB than changes in Ta or P alone (Table 5.6 a), though the basic trends are similar to the results from changes in Ta alone. But it is not a linear combination of effects resulted from changes in Ta and P respectively. Increase in Ta and decrease in P by 30% results in MB becoming a significant C source to the atmosphere, because of a dramatic decrease in moss GPP and increase in HR. Increase in Ta and 30% increase or decrease in P results in a large increases in shrub GPP and also shrub AR, leading to little change in shrub NPP. Increase in TER > GPP leads to decreases in NEP, but remaining positive, *i.e.* C sink, with small increase in Ta and an increase in P. However, the combination of increase in 2 to 5 ℃ Ta and 30% decrease in P makes MB becoming a C source to the atmosphere. Moreover, in spite of 30% increase in P, 5 ℃ increase in Ta still switches MB from a C sink to a C source.

We also conducted a sensitivity analysis for a combination of increase in Ta, 30% increase or decrease in P and doubled [CO_2] (Ta+P+CO_2) to examine the response of C cycling at MB to a fuller picture of future climate scenario (Table 5.6 a). The response of C cycling at MB to Ta+P+CO_2 is significantly different than changes in Ta or P or CO_2 alone and that of Ta+P. Increases in Ta and P with doubled [CO_2] result in significant increases in each component of NEP. The same analysis but with decreases in P produces an increase in each component of NEP, except moss GPP and AR, which drop considerably. With smaller increase in Ta, the effect of the doubling of [CO_2] offsets the changes leading to an increased uptake, but with larger increase in Ta and decrease in P the C sink is reduced and MB becomes a C source with 3 ℃ or more increase in Ta.

5.6.2 Degero Stormyr fen

Moss and sedge GPP decreases with increases or decreases in Ta with exception of the changes in 1 ℃ run (Table 5.6 b). Moss and sedge AR decrease with either increasing or decreasing Ta except with small increases in Ta. Oxic HR increases with increases in Ta and decreases with decrease in Ta, but anoxic HR decreases with increases or decreases in Ta. NEP decreases for all cases except 1 ℃ changes in Ta and with ≥+3 ℃ changes in Ta, the fen switches to a C source to the atmosphere.

The changes in moss, sedge and total GPP and AR are very small with changes in P (Table 5.6 b). Oxic and anoxic HR changes are also small with increases or decreases in P, with the exception of anoxic HR in the drier cases. NEP increases considerably as P decreases, while NEP decreases only slightly as P increases. Similar to results shown for bog, changes in P alone can not switch a fen to a C source to the atmosphere.

Similar to the case for a bog, all components, except anoxic HR, increase with a doubling of [CO_2] (Table 5.6 b). Therefore, doubled [CO_2] leads to a greater C sink for DS and enhances the peat accumulation.

Increases in Ta and 30% decrease in P decrease each component of NEP, except oxic HR which increases (Table 5.6 b). The decrease in total GPP > TER, so DS becomes a C source to the atmosphere. There is not a consistent pattern for the response of C cycling to increase in Ta and 30% increase in P. At small increase in Ta both moss and sedge GPP and AR increase, but the large increase in oxic HR leads to a decrease in NEP. At 5 ℃ change the moss and sedge GPP decrease. In this combination, DS becomes a source of C except for the +2 ℃ case, regardless of the changes in P.

The combination of increase in Ta and 30% decrease in P with a doubling of [CO_2] lead to a similar change as the T+P case (Table 5.6 a). But the moss and sedge can remain a positive NPP even with a 5 ℃ increase in Ta. However, as in the T+P combination, all but the +2 ℃ Ta and +30% P case, the NEP decreases and with the largest Ta increase regardless of P change the fen becomes a source of C, though the magnitude is partially offset by the doubling of [CO_2].

5.7 Discussions

The evaluation, conducted in this research by comparing the simulated C fluxes with observed ones, provides us with a confidence that CLASS3W-MWM can simulate the C cycling for both bogs and fens in northern peatlands reasonably well, though CLASS3W-MWM cannot reproduce the summer peak GPP for both bogs and fens well. Moreover, we acknowledge that the physical surface and soil climate simulated by CLASS3W-MWM is used as inputs to the simulation of C fluxes and will translate into the errors of the C fluxes.

Our modelling exercise shows that northern peatlands are thermally and hydrologically conservative ecosystems. Changes in air temperature do not translate directly into the same changes in peat temperature (Fig. 5.11). Changes in air temperature also lead to changes in soil moisture and thus water table depth, through changes in evapotranspiration. Particularly, large increases in air temperature causes a dramatic drop of water table depth (Fig. 5.11). Further, large changes in precipitation result in relatively small changes in water table depth, particularly in the fen (Fig. 5.12).

Fig. 5.11: The changes in peat T (℃) and WTD (cm) relative to the baseline simulated peat T and WTD responding to changes in air temperature (Ta: ℃). The top panel is for MB and bottom for DS.

Note: (1) Positive change in peat T means increase while negative decrease; positive change in WTD means increase (or drier) while negative decrease (or wetter). (2) Different scale for changes in WTD for MB and DS.

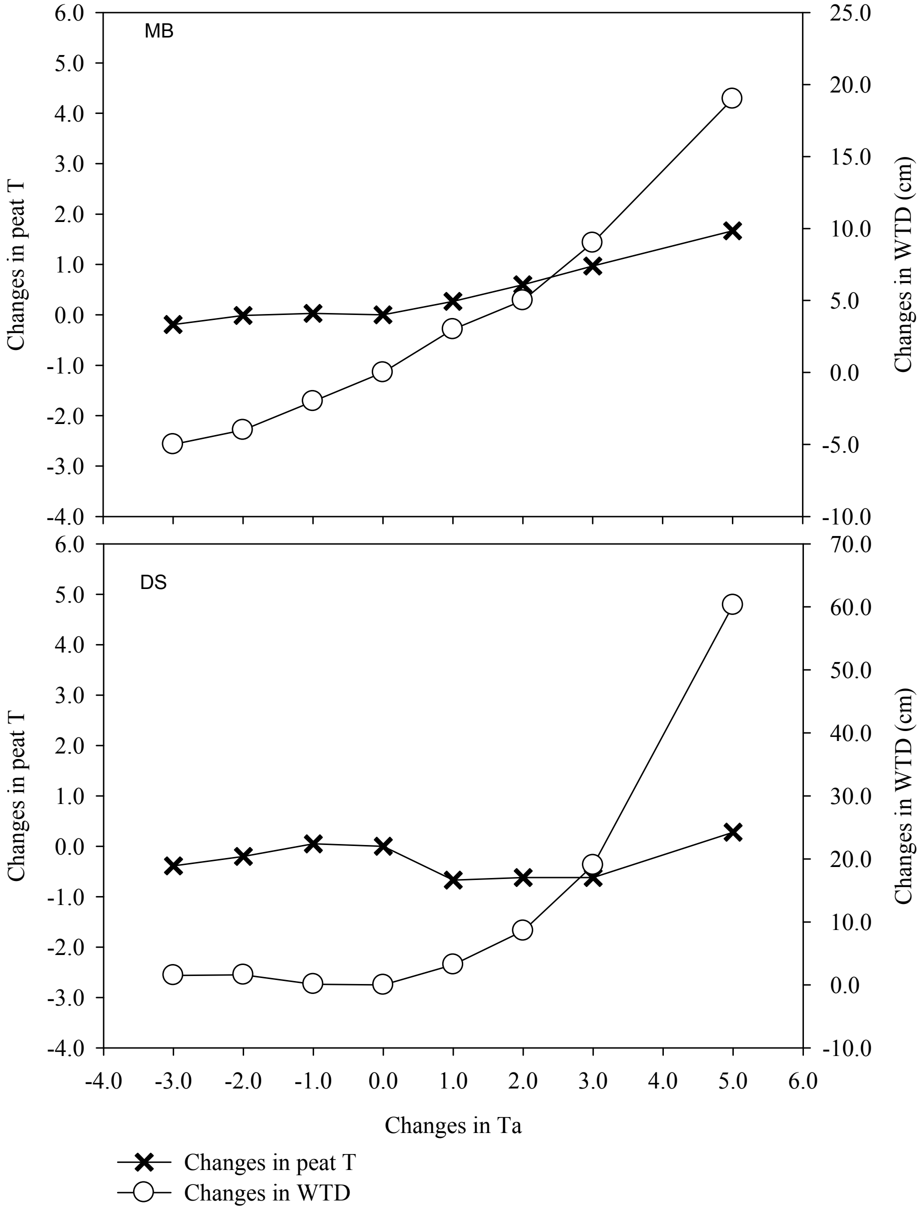
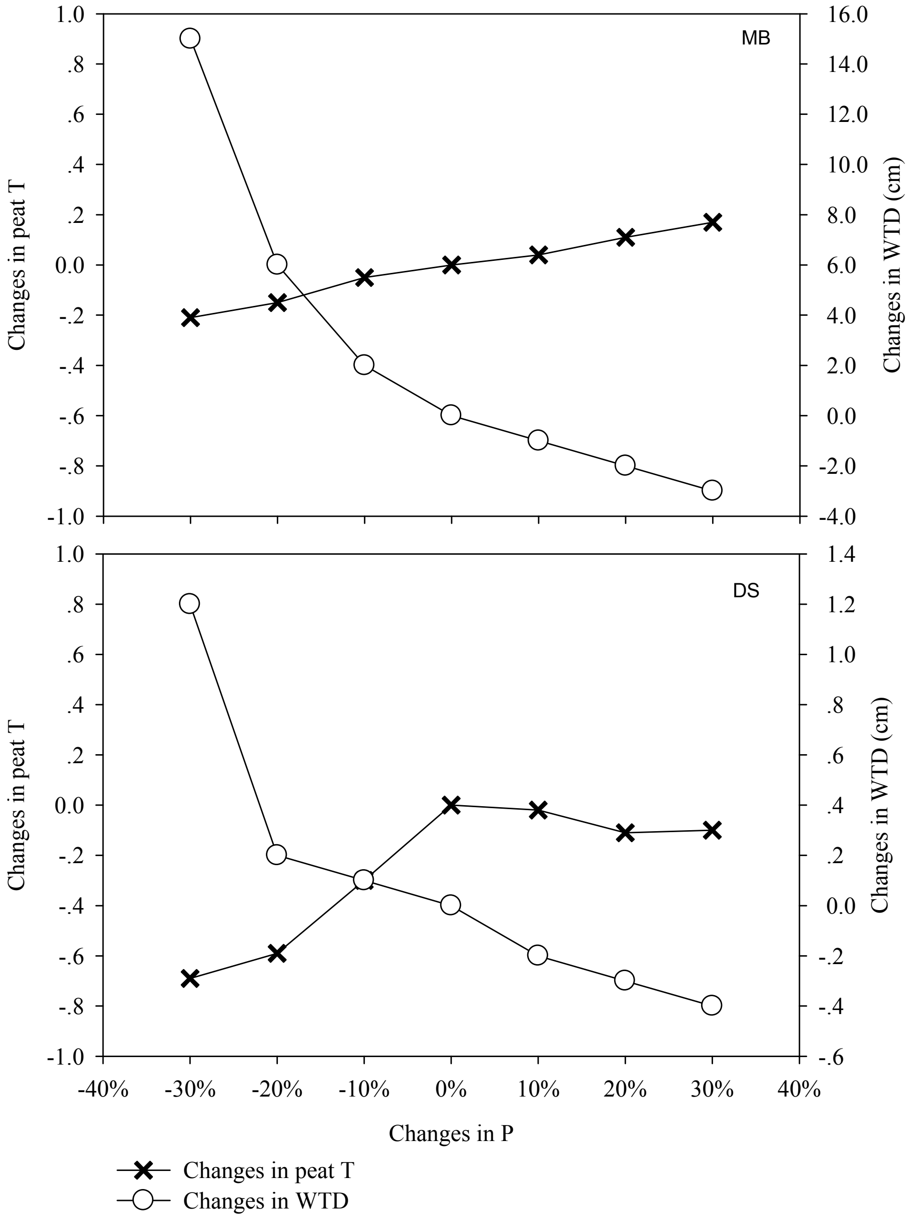


Fig. 5.12: The changes in peat T (℃) and WTD (cm) relative to the baseline simulated peat T and WTD responding to changes in precipitation (P). The top panel is for MB and bottom for DS.

Note: (1) Positive change in peat T means increase while negative decrease; positive change in WTD means increase (or drier) while negative decrease (or wetter). (2) Different scale for changes in WTD for MB and DS.



C cycling at a bog shows greater sensitivity to increases in air temperature than decreases in air temperature because increase in air temperature imposes some other constraints on C cycling through larger stress of canopy water content and soil moisture (represented by lower water table depth in Fig. 5.11). Moreover, respiration is an exponential function of air temperature (Frolking *et al.*, 2002; Lafleur *et al.*, 2005; St-Hilaire *et al.*, 2008), therefore, changes in air temperature lead to larger changes in TER than GPP. As a result, increases in air temperature can switch a bog to be a C source to the atmosphere.

The sensitivity to air temperature of the coupled CLASS3W-MWM contrasts with the results of the stand-alone MWM for both bogs (St-Hilaire *et al.*, 2008) and fens (Chapter 3). In CLASS3W-MWM soil climate is dynamically linked with surface climate, but changes in soil climate do not follow consistently and simultaneously changes in surface climate, reflected in changes in air temperature or precipitation (Fig. 5.11 and 5.12), because of the hydraulic and thermal properties of organic soil in peatland ecosystem (Comer *et al.*, 2000; Letts *et al.*, 2000; Parmentier *et al.*, 2009). For example, increases in air temperature result in increases in soil water stress (represented by increases in water table depth) (Fig. 5.11 and 5.12), which reduces the moss photosynthetic activity. Strack and Price (2009) and Tuittila *et al.* (2004) have empirically observed similar physical and biogeochemical changes with respect to changes in air temperature in the field. Our modelling exercise shows that moss GPP decreases as air temperature increases (Table 5.6 a and b). But stand-alone MWM cannot capture this, because changes in air temperature in stand-alone MWM do not affect the soil moisture at all.

Moreover, our sensitivity analysis shows that the fen is more vulnerable to environmental changes than the bog. A manipulative field experiment, which studied on the responses of C cycling in both bogs and fens to changes in water table depth and air temperature, showed a similar result (Bridgham *et al.*, 1995a; Bridgham *et al.*, 2008). Bogs have a large range of conditions which they appear to tolerate and continue to function reasonably normal with respect to a large range of environmental changes. But fens have a narrow or less resilence and therefore tend to change much more dramatically with respect to the same range of environmental changes.

Our sensitivity analysis also indicates that mosses on the bog are sensitive to climate changes. Empirical studies have shown similar results through changes in moss water content (*i.e.* moss capitulum moisture content) (Tuittila *et al.*, 2004; Strack and Price, 2009). It has been shown that both water table depth or moss capitulum moisture content can be used to predict moss C dynamics (Strack and Price, 2009). However, it is complicated to translate changes in precipitation into changes in moss capitulum moisture content and thus moss photosynthetic and respiration activity. Changes in moss function have been shown to occur without apparent changes in soil water content or water table position (Robroek *et al.*, 2009; Strack and Price, 2009). Roulet *et al.* (2007) speculated that the moss surface becomes effectively decoupled from the peat moisture content if water table depth is deeper than 35 cm. In CLASS3W-MWM we use both interception water from precipitation and moss capitulum water, which is a function of water table depth developed by Hayward and Clymo (1982), to represent the moss water dynamics. Due to the sensitivity of northern peatlands to moss function this is an important aspect for future study.

Our sensitivity analysis indicates that both moss and vascular plants in northern peatlands are sensitive to changes in the concentration of atmospheric CO_2. Specifically, the doubled CO_2 concentration results in increases in NEP and thus enhances peat accumulation. Field manipulations also showed a similar result, that elevated CO_2 enhances the height growth of moss but does not significantly influence the growth of vascular plant (Heijmans *et al.*, 2001). The CO_2 fertilization in northern peatlands is similar to that in other terrestrial ecosystems (Luo *et al.*, 2008; Balshi *et al.*, 2009), however in CLASS3W-MWM, moss AR does not respond to changes in CO_2 concentration (Table 5.6 a and b). Moss AR is related to maximum GPP, but not dynamically linked to the actual GPP. Therefore, moss AR is simulated by a function of air temperature and moss water content only. In addition, caution has to be made that the growth of moss and vascular plants does not have nutrient limitation in CLASS3W-MWM with the doubling of CO_2 concentration. But field study has shown that nutrient availability is important to constrain the effect of elevated CO_2 (Hoosbeek *et al.*, 2001).

Northern peatlands are located in a region that will be likely experiencing warmer and possibly drier climate in 21st century (IPCC, 2007; Meehl *et al.*, 2007). So the future climate change could have a significant impact on the hydrological and biogeochemical processes of northern peatlands (Bridgham *et al.*, 1995a; Belyea and Malmer, 2004; Bridgham *et al.*, 2008). Our sensitivity analysis shows that changes in air temperature, precipitation and the concentration of atmospheric CO_2 together result in a complex non-linear effect on the C cycling in northern peatlands. For example, decrease in precipitation exacerbates the decrease in NEP resulting from an increase in air temperature, while an increase in precipitation ameliorates the decrease in NEP resulting from an increase in air temperature. Moreover, CO_2 fertilization can compensate some of the decrease in NEP resulting from increase in air temperature and/or decrease in precipitation (Luo *et al.*, 2008; Balshi *et al.*, 2009). However, the sensitivity of C cycling in northern peatlands with respect to changes in air temperature, precipitation and the concentration of atmospheric CO_2 together is not a simple addition or subtraction of the sensitivity of the individual changes. Moore *et al.* (1998) had conjectured that non-linear relationship between hydrological and biogeochemical processes of northern peatlands introduces considerable uncertainties over how exactly northern peatlands respond to these changes. Our results indicate that it is critical to examine the sensitivity of C cycling in northern peatlands that the contribution of changes in air temperature, precipitation and the concentration of atmospheric CO_2 be considered. CLASS3W-MWM could be used to do a factorial analysis to examine the relative role of changes in air temperature, precipitation and CO_2 concentration in maintaining northern peatlands as a C sink or switching northern peatlands to be a C source to the atmosphere (*e.g.* Luo *et al.*, 2008), but this is beyond the scope of this present study. Our sensitivity analysis indicates that northern peatlands are very sensitive to increases in air temperature and doubling of the CO_2 concentration. These synergies should be considered when field manipulative experiments are designed.

We acknowledge that CLASS3W-MWM has a number of limitations. Firstly, CLASS3W-MWM assumes fixed vegetation. There is no change in the structure of vegetation communities with changes in environmental changes. However, plant communities in northern peatlands do change when they are, in particular, subjected to significant changes in moisture (Weltzin *et al.*, 2000; Weltzin *et al.*, 2001; Weltzin *et al.*, 2003). Secondly, our sensitivity analysis shows that fens seem to be more sensitive to environmental changes, but we have assumed changes in precipitation only and fens are also influences by lateral exchanges in water. Therefore, it is needed to put fens into the context of their catchment, as in the study of Sonnentag (2008).

5.8 Conclusions

To simulate the sensitivity of C cycling in northern peatlands to projected climate change, McGill Wetland Model (MWM) was coupled to a land surface climate model, *i.e.* wetland version of Canadian Land Surface Scheme (CLASS3W). In this paper, we evaluated this coupled model for a bog (MB) and a fen (DS) by comparing the simulated NEP with the observed NEP from an eddy-covariance tower. CLASS3W-MWM simulates the magnitude, direction, seasonal and inter-annual variability of CO_2 fluxes reasonably well for both MB and DS, though summer peak GPP and TER are not reproduced well. The statistical indices for the daily comparison have shown that the performance of CLASS3W-MWM for the simulation of C fluxes in northern peatlands based on the simulated soil and surface climate (r^2=0.63, 0.42; d*=0.88, 0.80; RMSE=0.54, 0.54 for MB and DS respectively) is comparable to that of stand-alone MWM based on the observed soil and surface climate (r^2=0.58, 0.52; d*=0.80, 0.84; RMSE=0.21, 0.49 for MB and DS respectively).

Our sensitivity analysis based on CLASS3W-MWM confirms that northern peatlands are thermally and hydrologically conservative ecosystems. There are significant differences between the sensitivity analysis based on CLASS3W-MWM and that based on a stand-alone MWM. Both bogs and fens can switch from the present C sinks to C sources within the range of climate changes proposed by IPCC report. This is due to both increased autotrophic and heterotrophic respiration. But for fen, decreased photosynthesis does play a role as well due to the extreme dry or wet condition. Moreover, both bogs and fens are more sensitive to changes in air temperature than precipitation. However, fens are more sensitive to environmental changes than bogs. Though both bogs and fens are very vulnerable to drought, resulting from either increase in air temperature or decrease in precipitation, only changes in precipitation do not switch northern peatlands to be a C source to the atmosphere. Moreover, our sensitivity analysis based on the combination of the individual change suggests that northern peatlands respond to changes in air temperature, precipitation and CO_2 concentration in a highly non-linear way.

Connecting statement

Chapter 5 showed that CLASS3W-MWM captures the magnitude and direction of CO_2 fluxes for both the Mer Bleue bog and the Degero Stormyr fen and reproduces the seasonal and inter-annual variability, though peak summer GPP and AR were not captured very well. The performances of CLASS3W-MWM for the simulation of C fluxes in northern peatlands based on the simulated soil and surface climate are similar to that of the stand-alone MWM based on the observed soil and surface climate. However, there are significant differences between the sensitivity analysis of the coupled CLASS3W-MWM and the stand-alone MWM. Furthermore our sensitivity analysis illustrated that northern peatlands respond to changes in air temperature, precipitation and CO_2 concentration in a highly non-linear way and the sensitivity of combination of changes in temperature, precipitation and double CO_2 concentration is much different than the sensitivity of peatlands to each environmental variable on its own.

In Chapter 6, we use the coupled CLASS3W-MWM to simulate the response of the C cycling in northern peatlands to the projected climate changes simulated by CCCma CGCM3.0 over the 21st century. Four IPCC climate change scenarios are used (A1B, A2, B1 and Commit) at three time slices (2030, 2060 and 2100) for this study.

Chapter 6 Northern peatlands still function as carbon sinks, but can switch to carbon sources as well under the changing climate up to 2100

This chapter is based on a manuscript in preparation entitled:

Jianghua Wu and Nigel Roulet, Northern peatlands currently function as carbon sinks, but could switch to carbon sources before 2100 due to climate change.

6.1 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, equivalent to half of the mass of atmospheric C (IPCC, 2007). Moreover, northern peatlands contribute about 10% to global natural methane 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^{-2} yr^{-1}) (Lafleur *et al.*, 2003; Roulet *et al.*, 2007; Nilsson *et al.*, 2008; Sagerfors *et al.*, 2008).

In northern peatlands, hydrology and biogeochemistry are tightly coupled to climate (Holden, 2005; Bridgham *et al.*, 2008; Ise *et al.*, 2008; Frolking *et al.*, in press). 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 latitudes (Meehl *et al.*, 2007). This raises concerns over whether northern peatlands will remain C sinks under climate change.

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, it is expected that bogs and fens 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 counted as important as water table. Balshi *et al.* (2009) simulated that without considering the interactive changes in CO_2 concentration boreal forests function as small C sources to the atmosphere, but inclusion of changes in CO_2 concentration the boreal forest is a C sink by 2100. 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).

In this study, we used a coupled land surface climate and a peatland C model, called CLASS3W-MWM (Chapter 5), to simulate the response of the C cycling in northern peatlands to the projected climate changes over the 21st 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, Degero Stormyr (DS) in Northern Sweden under the present climate (Chapter 5). Here, we used CLASS3W-MWM to simulate the CO_2 fluxes at MB and DS under projected climates simulated by CCCma CGCM3.0 (Flato and Boer, 2001; Kim *et al.*, 2002) for 4 IPCC emission scenarios (A1B, A2, B1 and Commit) for 3 time slices (2030, 2060 and 2100) of the transient climate simulations. Our results show that these two northern peatlands may remain C sinks through to 2100, though in the two scenarios showing greatest changes (A1B and A2) the fen switches to a C source.

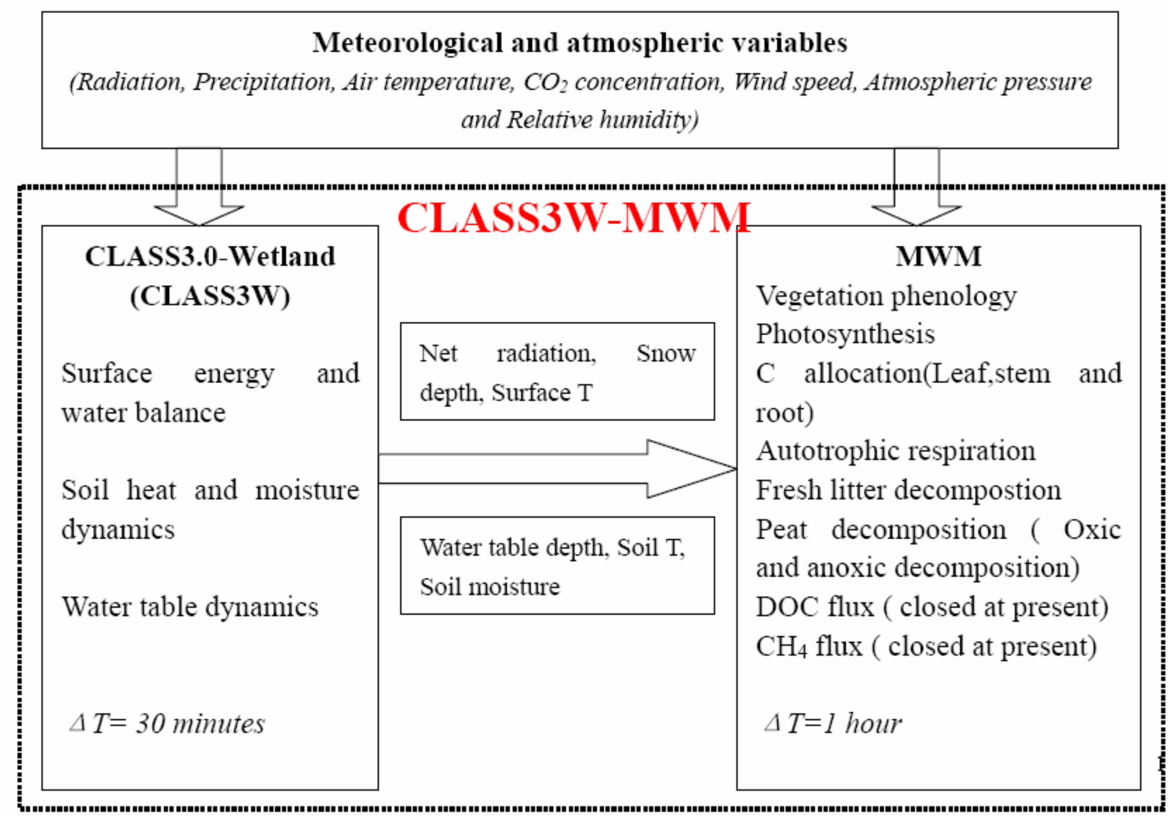
6.2 Methods

6.2.1 The CLASS3W-MWM framework

In this modelling study, CLASS3W-MWM (Chapter 5) was used to simulate the surface and soil climate and the C cycling in northern peatlands. The land surface climate component, *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 (Fig. 6.1). Then, the C cycling component, *i.e.* MWM, 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 requires the following inputs: air temperature, precipitation, wind speed, solar radiation, specific humidity, and atmospheric pressure and CO_2 concentration.

CLASS3W-MWM solves total runoff, including surface overland runoff, subsurface and peatland lateral flow and groundwater seepage, latent, sensible and ground heat flux, temperature and water content for 3 soil layers, water table depth, carbon storage in leaves, stems and roots, 1 soil C pool and 1 fresh litter C pool that decomposes much faster than soil C pool. The detailed model description can be found in Verseghy (1991), Verseghy *et al.* (1993) and Letts *et al.* (2000) for the land surface model component, and St-Hilaire *et al.* (2008) and Chapter 3 for the C cycling model component.

Fig. 6.1: The basic structure of CLASS3W-MWM.



In CLASS3W-MWM, the soil hydrology was outlined in Verseghy (1991). Parameterization of hydraulic properties for peatland soil (or organic soil) was introduced by Letts *et al.* (2000). A water content form of Richard equation (Jury and Horton, 2004), is solved using classic soil-water characteristics curves, and unsaturated hydraulic conductivity is a function of soil water content (Campbell, 1974). A simple hydrological scheme was added to convert the distribution of soil moisture to a water table depth (WTD) based on the saturated soil volume and specific yield and retention (Letts *et al.*, 2000). These modifications worked well for fens (Comer *et al.*, 2000; Letts *et al.*, 2000), but for bogs a lateral outflow was added to update the soil water dynamics in order to simulate the water table depth properly (Ouyang *et al.*, in press).

In CLASS3W-MWM, there are 4 plant function types (PFT) - trees, shrubs, sedges, and mosses, to represent the vegetation communities in northern peatlands. Carbon enters peatland ecosystem through photosynthesis by vascular plants, mosses and trees, if trees are present. Carbon is lost from this system through autotrophic respiration (AR) of plants， decomposition of fresh litter, and soil decomposition, *i.e.* heterotrophic respiration (HR). Photosynthesis in vascular plants is simulated for each PFT by a Farquhar biochemical approach (Farquhar *et al.*, 1980; Farquhar and von Caemmerer, 1982), coupled with canopy-level stomata conductance (Jarvis, 1976; Ball *et al.*, 1987) to solve an optimal PFT-specific GPP. For mosses a semi-empirical function including the effect of moss water content on photosynthetic capacity (Tenhunen *et al.*, 1976) and on total conductance of CO_2 (Williams and Flanagan, 1998) is used to replace the stomata conductance. For a fen peatland, the optimal GPP is constrained by a non-linear function of WTD to compute the actual GPP rate (Chapter 3). The fixed carbon is allocated to leaves, stems and roots, following Frolking, *et al* (2002). A simple degree day approach is used for the vegetation phenology (Frolking *et al.*, 2002; St-Hilaire *et al.*, 2008). AR is composed of maintenance and growth respiration. HR is the sum of fresh litter decomposition and peat soil decomposition. Peat soil decomposition is calculated based on 2 soil carbon compartments, *i.e.* oxic C storage above WTD and anoxic C storage below WTD. For a bog peatland, the oxic and anoxic zone is subdivide by an effective WTD based on the actual WTD (St-Hilaire *et al.*, 2008), while for a fen because the roots of sedge penetrate below the WTD the effective WTD is calculated from a non-linear function of sedge net primary production (NPP) (Chapter 3).

6.2.2 Study sites

This modelling study was conducted on two peatlands (Table 6.1 and 6.2): Mer Bleue (MB), an ombrotrophic bog, and Degero Stormyr (DS), a minerotrophic poor fen. CLASS3W-MWM was configured and initialized for MB and DS respectively to do the C cycle simulation (Table 6.3).

Table 6.1: The detailed description of the study sites, *i.e.* Mer Bleue (MB) and Degero Stormyr (DS).

Characteristics	**Bog (MB)**	**Fen (DS)**
Name	Mer Bleue	Degero Stormyr
Location	45.41°N, 75.48°W, eastern Canada	64°11’N, 19°33’E, northern Sweden
Climate	Cool continental temperate	Cold temperate humid
Peatland classification	Ombrotrophic bog	Minerotrophic poor fen
Nutrients	Poor	Rich
Water sources	Precipitation	Precipitation, surface runoff and groundwater
Size	28 km^2	6.5 km^2
Depth of peat	5-6m	3-4m
Basal age	~9000 yrs	~8000 yrs
Dominant plants	Moss and Shrubs	Moss and Sedges
Surface topography	69 m a.m.s.l	270 m a.m.s.l

Table 6.2: The 40-year (*i.e.* 1961-2000) average climate for MB and DS.

Note: Ta: air temperature; P: precipitation.

Characteristics	**Bog (MB)**	**Fen (DS)**
Mean annual Ta (℃)	6.0	1.2
Monthly max. Ta (℃)	20.9	14.7
Monthly min. Ta (℃)	-10.8	-12.4
Days above 0 ℃	206.0	150.0
Mean annual P (mm)	943.0	523.0
Precipitation as snow (mm)	235.0	233.0
Monthly max. P (mm)	90.0	65.0
Monthly min. P (mm)	60.0	25.0

Table 6.3: Parameters and initial values used in CLASS3W-MWM for MB and DS.

Parameter	**Bog(MB)**	**Fen(DS)**	**Units**	**Description**	**Reference/Source**
Values for Model Parameters at 25°C					
J_{max}:V_{max}	1.67	1.67	-	ratio	(Medlyn *et al.*, 2002)
Mosses					
V_{cmax25}	6	6.5	μ mol $m^{-2}s^{-1}$	max carboxylation rate (spring)	
	14	14	μ mol $m^{-2}s^{-1}$	max carboxylation rate (summer)	
	7	7.5	μ mol $m^{-2}s^{-1}$	max carboxylation rate (autumn)	
R_{d25}	0.946	0.946	μ mol $m^{-2}s^{-1}$	dark respiration rate	(Harley *et al.*, 1986)
Shrubs/Sedges					
V_{cmax25}	17	20	μmol $m^{-2}s^{-1}$	max carboxylation rate	
Initial site specific parameters					
frac	48.7	48.7	%	biomass to carbon ratio	
B_{moss}	140	150	g biomass m^{-2}	moss capitula biomass	
$B_{min\ foliar}$	175	90	g biomass m^{-2}	min shrub/sedge foliar biomass	
$B_{max\ foliar}$	350	180	g biomass m^{-2}	max shrub/sedge foliar biomass	
LAI_moss	1.35	1.05	m^2/m^2	initial moss leaf area idex	
LAI_shrub/Sedge	0.9	0.5	m^2/m^2	initial shrub/sedge leaf area index	
Root_shrub/sedge	500	450	g biomass m^{-2}	Initial shrub/sedge root biomass	
Litter_shrub/sedge	150	250	g biomass m^{-2}	Initial shrub/sedge litter biomass	
B_{stem}	0.003		$m^3\ m^{-2}$	shrub sapwood volume	
PD_0	6	4	m	initial peat depth	
k_o	0.05/0.2	0.05/0.2	y^{-1}	initial decomposition rate for moss/shrub(sedge)	(Frolking *et al.*, 2001)

Initial values for organic soil					
Z	0.20/0.75/6.0	0.20/0.75/4.0	m	Depth to bottom of 3 soil layers	(Ouyang *et al.*, in press)
θp	0.93/0.88/0.83	0.93/0.88/0.83		Porosity for 3 soil layers	(Letts *et al.*, 2000)
θr	0.175/0.530/0.705	0.175/0.530/0.705		Specific retention for 3 soil layers	(Letts *et al.*, 2000)
θm	0.04/0.15/0.22	0.04/0.15/0.22		Residual soil water content for 3 soil layers	(Letts *et al.*, 2000)
b	2.7/6.1/9.5	2.7/6.1/9.5		Soil texture parameter	(Letts *et al.*, 2000)
Ψs	9.6E-3/9.06E-3/8.3E-3	9.6E-3/9.06E-3/8.3E-3	m	Soil matric potential at saturation	(Ouyang *et al.*, in press)
γ	1.7E-4/2.0E-6/1.0E-8	1.7E-4/2.0E-6/1.0E-8	$m\ s^{-1}$	Hydraulic conductivity at saturation	(Ouyang *et al.*, in press)

6.2.2.1 Mer Bleue bog

Mer Bleue, located 10 km east of Ottawa, Ontario, Canada (45.41° N, 75.48° W, 69 m a.m.s.l), in a postglacial channel, began to accumulate organic matter in 9000 a B.P. and switched to a bog phase around 7100-6800 years ago (Table 6.1) (Auer, 1930; Mott and Camfield, 1969). The climate of the region, where MB is located, is classified as cool continental temperate. The detailed 40-year (1961-2000) average climate is shown in Table 6.2.

MB is a 28 km^2 ombrotrophic bog (Table 6.1) (Moore *et al.*, 2002; Lafleur *et al.*, 2003; Roulet *et al.*, 2007). The dominant evergreen (*Chamaedaphne calyculata,Ledum groenlandicum, Kalmia angustifolia*), and deciduous (*Vaccinium myrtilloides*) shrubs have an average height of 20-30 cm and leaf area index (LAI) of ~1.3 (one-sided) (Moore *et al.*, 2002; Bubier *et al.*, 2006). Sedges (*Eriophorum vaginatum*) comprise a sparse cover and a few small trees (*Picea mariana, Larix laricina, Betula populifolia*) are present on hummocks. The surface is covered by *Sphagnum* mosses (*S. capillifolium, S. magellanicum, S. Fuscum*). However, 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 ± 100 g m^{-2} (Moore *et al.*, 2002) and 433 g m^{-2} (Bubier *et al.*, 2006) respectively, and total belowground biomass, measured in 1999, was 1820 ± 660 g m^{-2}. *Sphagnum* capitulum biomass was 144 ± 30 g m^{-2} in 1999 (Moore *et al.*, 2002) and 158 g m^{-2} in 2004 (Bubier *et al.*, 2006).

6.2.2.2 Degero Stormyr fen

Degerö Stormyr (DS) , located in Northern Sweden (64°11’N, 19°33’E), is an acid, oligotrophic, minerogenic, mixed mire system covering 6.5 km^2 (Table 6.1 and 6.2) (Sagerfors, 2007; Sagerfors *et al.*, 2008). The mire consists of interconnected smaller mires divided by islets and ridges of glacial till and is situated between two rivers. The depth of the peat is generally between 3-4 m, but depths up to 8 m have been found. The deepest peat corresponds to an age of ~8000 years. The climate of the region is defined as cold temperate humid (Table 6.1). The detailed 40-year (1961-2000) average climate is shown in Table 6.2.

The vascular plant community (Table 6.1) is dominated by *Eriophorum vaginatum* L.*, Vaccinium oxycoccos* L.*, Andromeda polifolia* L.*,Rubus chamaemorus* L. with both *Carex limosa* L. and *Schezeria palustris* L. occurring more sparsely. *Carex rostrata* L. is found within the margins of this fen, where there is a direct minerogenic water inflow. The surface vegetation in the wet carpets is dominated by *Sphagnum majus* Russ. C. Jens*,* and the lawns by *S. balticum* Russ. C. Jens. and *S. lindbergii* Schimp, while *S. fuscum* Schimp. Klinggr. and *S. rubellum* Wils. are dominant on the hummocks.

6.2.3 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). 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 4 IPCC proposed emission scenario-A1B, A2, B1 and Commit. The general characteristics of the four scenarios are shown in Table 6.4. We chose three time slices- 2030, 2060 and 2100 for this study.

Table 6.4: The general characteristics for the four chosen IPCC emission scenarios in this study and the global mean warming from multi-model (CCCma CGCM3.0 was included) ensemble mean for 4 time periods relative to 1980-1999 for each of the 4 scenarios (IPCC, 2007).

Note: $[CO_2]$: the concentration of atmospheric CO_2.

	Characteristics	**A1B**	**A2**	**B1**	**Commit**
General features	Economic growth	Very rapid	Very heterogeneous with local identity	Medium	Commit to reduce GHG
	Technological development	Rapid	Slow	Medium	Commit to reduce GHG
	Global convergence	Slow	Slow	Fast	Fast
	Energy use	High	High	Medium	Low
	Environmental sustainablity	N/A	N/A	Yes	Yes
	Global population	Peak in mid-century	15 billion by 2100	Same as A1B	N/A
$[CO_2]$ (ppm)	Present-day	380.00	380.00	380.00	380.00
	2030	460.00	450.00	440.00	380.00
	2060	570.00	580.00	500.00	380.00
	2100	720.00	800.00	550.00	380.00
Global mean warming	Present-day	0.00	0.00	0.00	0.00
	2011-2030	0.69	0.64	0.66	0.37
	2046-2065	1.75	1.65	1.29	0.47
	2080-2099	2.65	3.13	1.79	0.56
	2180-2199	3.36	N/A	2.10	N/A

For simulations of the ecosystem model driven by future climate, it is 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 6.1 for temperature and equation 6.2 for precipitation) to do the simulation:

$$\mathit{CGCM3\_Adjust}=\mathit{Climate\_Present}+(\mathit{CGCM3\_Future}-\mathit{CGCM3\_Mean}), \tag{6.1}$$

$$\mathit{CGCM3\_Adjust}=\mathit{Climate\_Present}\times(\mathit{CGCM3\_Future}/\mathit{CGCM3\_Mean}), \tag{6.2}$$

where $\mathit{CGCM3\_Adjust}$ was the adjusted future climate for 2030, 2060 and 2100; $\mathit{Climate\_Present}$ was the present time climate from 1999-2006 for MB and from 2001-2006 for DS; $\mathit{CGCM3\_Future}$ was the future projected climate from CGCM3 (*e.g.* 2030, 2060 and 2100) and $\mathit{CGCM3\_Mean}$ was the mean climate from 1961-2000 also from CGCM3. 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 in one month on the half-hourly observed climate data.

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. But we assumed that the difference between the future projected global mean CO_2 concentration for the three time slices (Table 6.4) and the present day global mean CO_2 concentration (*i.e.* 380 ppm) was imposed on the half-hour observation of CO_2 concentration.

We also used equation 6.1 and 6.2 to derive the baseline input climates for CLASS3W-MWM as follows. The difference between the simulated average climate for 1999-2006 for the grid cell where MB is located and 2001-2006 for the grid cell where DS is located from CGCM3.0 and the simulated mean climate for 1961-2000 also from CGCM3.0 was imposed on the observed half-hour weather for 1999-2006 for MB and 2001-2006 for DS respectively. 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 the simulated baseline CO_2 fluxes.

6.2.4 Model spin-up

The peat decomposition model (PDM) (Frolking *et al.*, 2001) was used to initialize the present-day vertical profile of mass loss rates for the bog and the fen respectively for CLASS3W-MWM (St-Hilaire *et al.*, 2008, and Chapter 3, 5). The vertical profile was developed using a long-term constant water table depth of a representative bog and fen, but a modifier representing the effect of anoxic condition on decomposition was applied in PDM (St-Hilaire *et al.*, 2008). In CLASS3W-MWM, a different modifier, *i.e.* 0.1 and 0.025, was used for a bog and fen, respectively. Then for CLASS3W-MWM the effective oxic and anoxic decomposition rates for a bog and fen were derived by integrating the decomposition curve of the vertical profile in oxic and anoxic zone respectively in

PDM. The effective oxic and anoxic decomposition rates for a bog and fen were kept as constant to compute the oxic and anoxic decomposition for MB and DS respectively for the whole simulation period (Chapter 5).

6.3 Results

Three soil layers' temperatures (SoilT1, SoilT2 and SoilT3 :℃) and water table depth (WTD: m below surface), are the simulated physical outputs based on CGCM3.0 derived climate inputs. The simulated surface and soil climate are then inputs to the C cycle simulation where the CO_2 fluxes - gross primary production (GPP), total ecosystem respiration (TER) and net ecosystem exchange (NEE=GPP-TER), between peatlands and the atmosphere are the outputs (Chapter 3 and 5). 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 indicates C uptake by peatlands, while negative NEP means C emission to the atmosphere.

6.3.1 Mer Bleue bog (MB)

6.3.1.1 Environmental variables

For all scenarios except Commit, Ta rose continuously to 2100, though the rate of increase varied slightly among scenarios (Fig. 6.2: left column). The increases in Ta in the spring were a little bit larger than those in other seasons (Fig. 6.3: left column). Most of the increases in monthly Ta were <5.0 ℃, but increases of >6.0 ℃ also occurred in the spring season for A1B and A2 (Fig. 6.3: left column).

For all scenarios, the annual P was increased (*i.e.* ΔP>0) to 2100 (Fig. 6.2: left column), though the changes in monthly P showed no consistent pattern among scenarios (Fig. 6.3: right column). Further, increase and decrease in P existed over all the months (Fig. 6.3: right column). The increase in P was normally larger in the spring and winter than that in the summer.

In this modelling exercise, soilT, soil moisture and WTD were simulated through solving the soil energy and water balance. For all scenarios except Commit, soilT rose up continuously to 2100 with a range of 1-2 ℃. The range of increases in soilT was ~ 1/3 of that for Ta. Desipte a 200-300 mm increase in annual P, because of increase in evapotranspiration, water table depth (WTD) increased only by up to 10 cm by 2100, 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).

Fig. 6.2: The CGCM3.0 simulated climate (Ta (℃): air temperature; P (mm): precipitation) and CLASS3W-MWM simulated soil climate (3 layers' soil temperature (℃): SoilT1, SoilT2 and SoilT3; WTD (m): water table depth (below surface)) for baseline, 2030, 2060 and 2100 respectively.

Left is for Mer Bleue (MB) and right for Degero Stormyr (DS). From top to bottom are for A1B, A2, B1 and Commit respectively. (See next page)

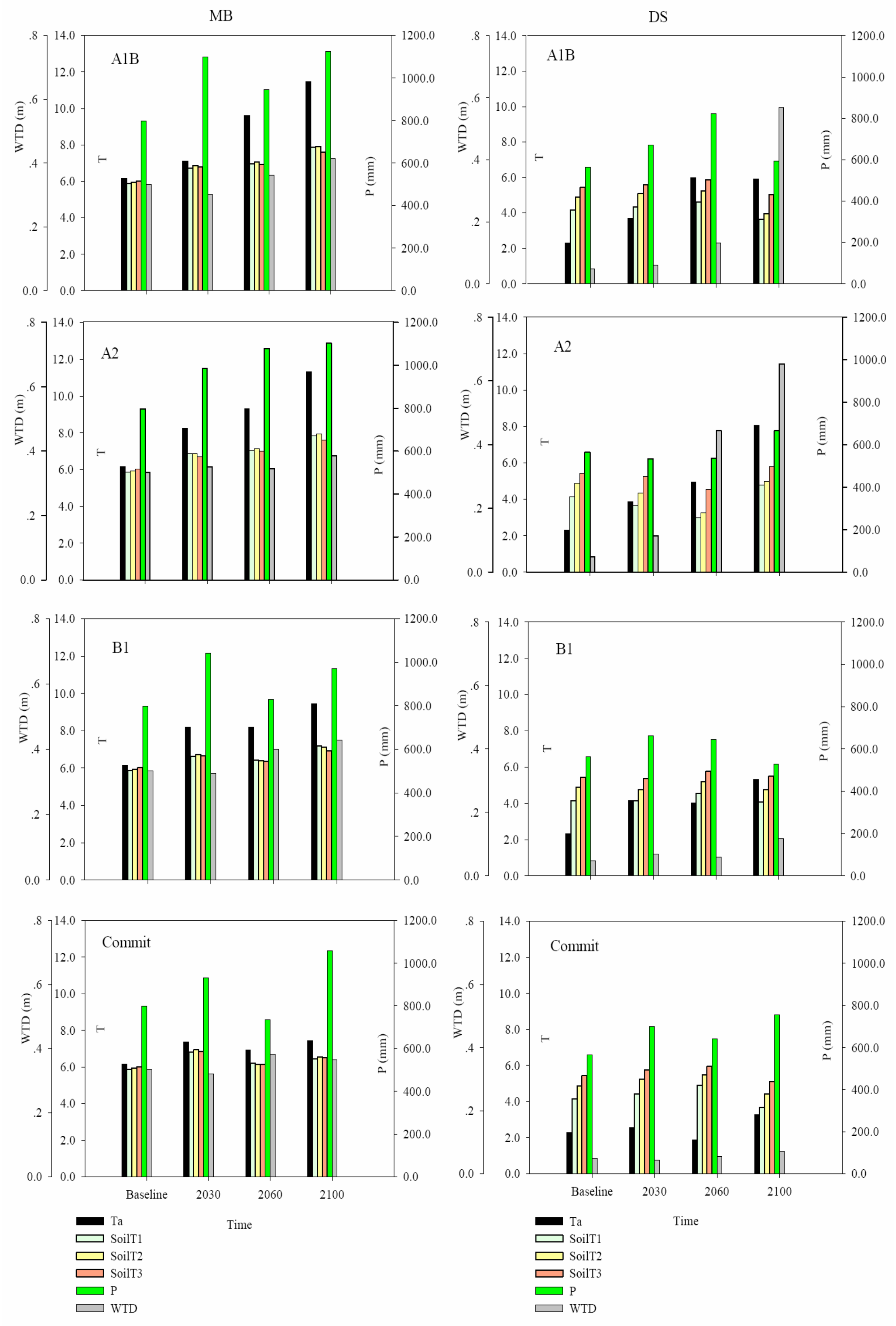

MB
DS
A1B
A2
B1
Commit
WTD (m)
T
P (mm)
0.0
.2
.4
.6
.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0
Baseline
2030
2060
2100
Time
Ta
SoilT1
SoilT2
SoilT3
P
WTD

Fig. 6.3: The monthly changes in CGCM3.0 simulated Ta (℃) and P (%) for 2030, 2060 and 2100 relative to the 40 years' average from 1961-2000 at MB.

Left is for Ta and right for P. From top to bottom are for A1B, A2, B1 and Commit respectively. The baseline Ta and P is inserted in the top left and right box respectively. (See next page)

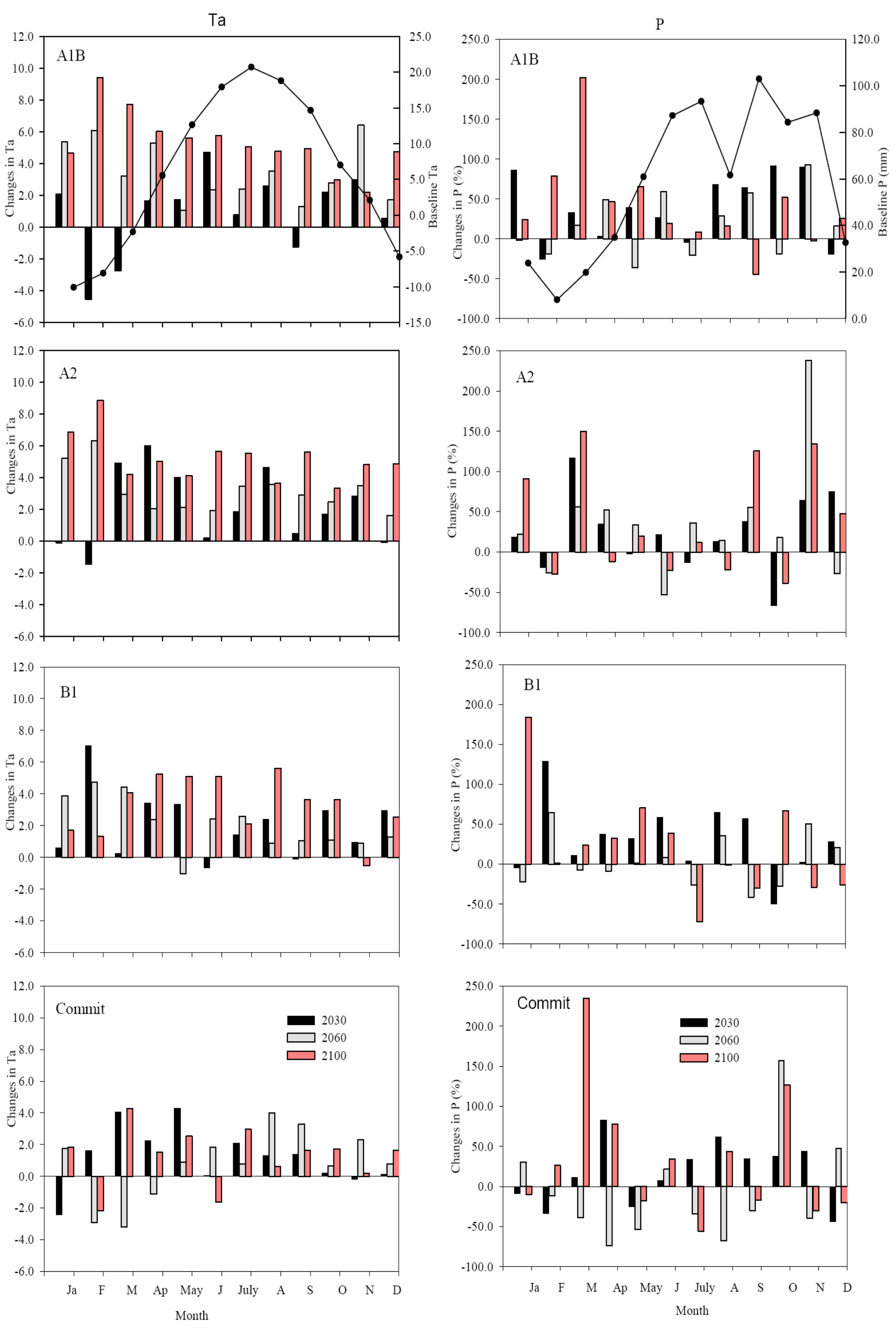

Ta
P
A1B
A2
B1
Commit
Changes in Ta
Baseline Ta
Changes in P (%)
Baseline P (mm)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
250.0
200.0
150.0
100.0
50.0
0.0
-50.0
-100.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
2030
2060
2100
Ja
F
M
Ap
May
J
July
A
S
O
N
D
Month

Table 6.5: The number of days with daily Ta > 0.0℃ and Ta > 4.0 ℃ for the baseline, 2030, 2060 and 2100 for the four selected scenarios in this study: (a) for MB; (b) for DS.

(a) MB

	A1B(>0.0)	A1B(>4.0)	A2(>0.0)	A2(>4.0)	B1(>0.0)	B1(>4.0)	Commit(>0.0)	Commit(>4.0)
Baseline	*255*	*209*	*255*	*209*	*255*	*209*	*255*	*209*
2030	257	226	272	241	276	235	264	225
2060	291	257	286	247	281	236	253	214
2100	301	269	304	268	274	238	270	229

(b) DS

	A1B(>0.0)	A1B(>4.0)	A2(>0.0)	A2(>4.0)	B1(>0.0)	B1(>4.0)	Commit(>0.0)	Commit(>4.0)
Baseline	*207*	*160*	*207*	*160*	*207*	*160*	*207*	*160*
2030	228	179	222	171	237	183	214	165
2060	276	219	251	194	226	176	203	163
2100	272	208	303	248	260	200	222	170

In CLASS3W-MWM, a simple degree-day approach was used to define the phenology for moss and vascular plants (St-Hilaire *et al.*, 2008). We calculated the number of days with Ta > 0.0 ℃ and 4.0 ℃ to represent the length of growing period for moss and vascular plant respectively (Table 6.5 a). For all scenarios except Commit, the length of growing period for moss and vascular plant increased up to 2100. The increase for A1B and A2 (45-50 days) was much larger than B1 (~19 days). Under Commit scenario, there was only a marginal variation over time.

In summary, MB will be generally warmer and slightly drier with larger growing periods and the difference between the four scenarios is smaller than the differences in all scenarios between present-day, 2030, 2060 and 2100.

6.3.1.2 CO_2 exchanges

For all scenarios except Commit, GPP was enhanced by 151-262 g C m^{-2} yr^{-1} up to 2100, although the magnitude and trend of increase varied over time among scenarios (Fig. 6.4). 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.

Fig. 6.4: The CLASS3W-MWM simulated CO_2 fluxes (GPP, TER and NEP) at MB for Baseline, 2030, 2060 and 2100 for A1B, A2, B1 and Commit respectively.

From top to bottom are for GPP, TER and NEP respectively. The unit is g C m^{-2} yr^{-1}.

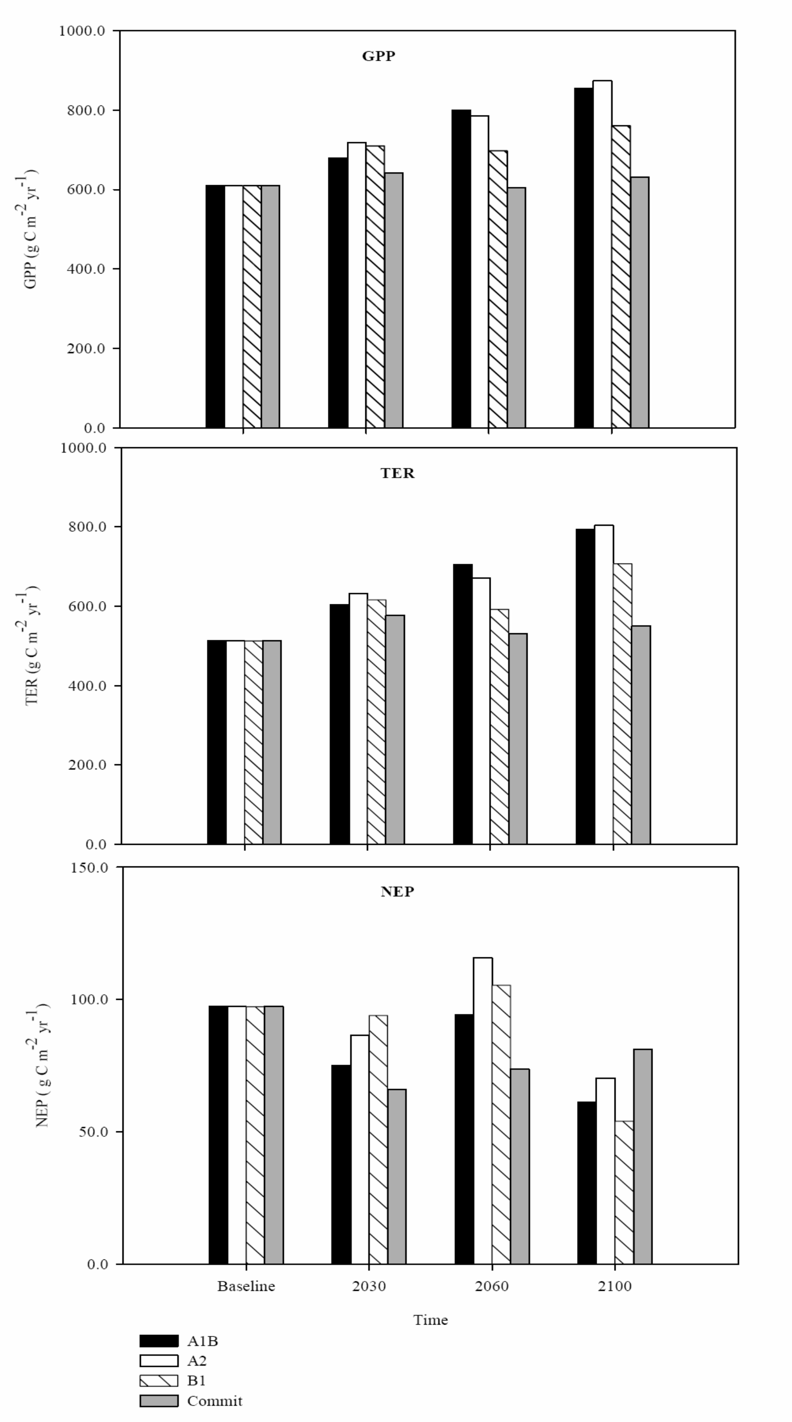


Fig. 6.5: The CLASS3W-MWM simulated components (AR: autotrophic respiration; oxic HR: oxic decomposition; anoxic HR: anoxic decomposition; HR (heterotrophic respiration) =oxic HR+anoxic HR) of TER (=AR+HR) at MB for Baseline, 2030, 2060 and 2100 for A1B, A2, B1 and Commit respectively. The unit is g C m^{-2} yr^{-1} .

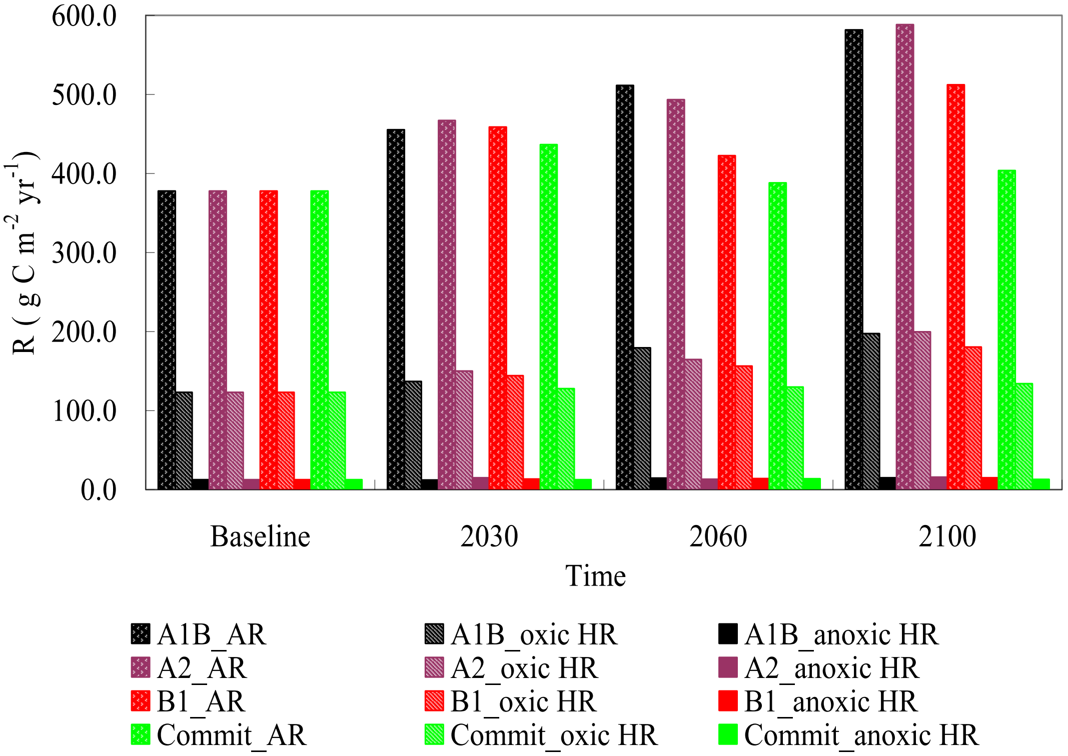
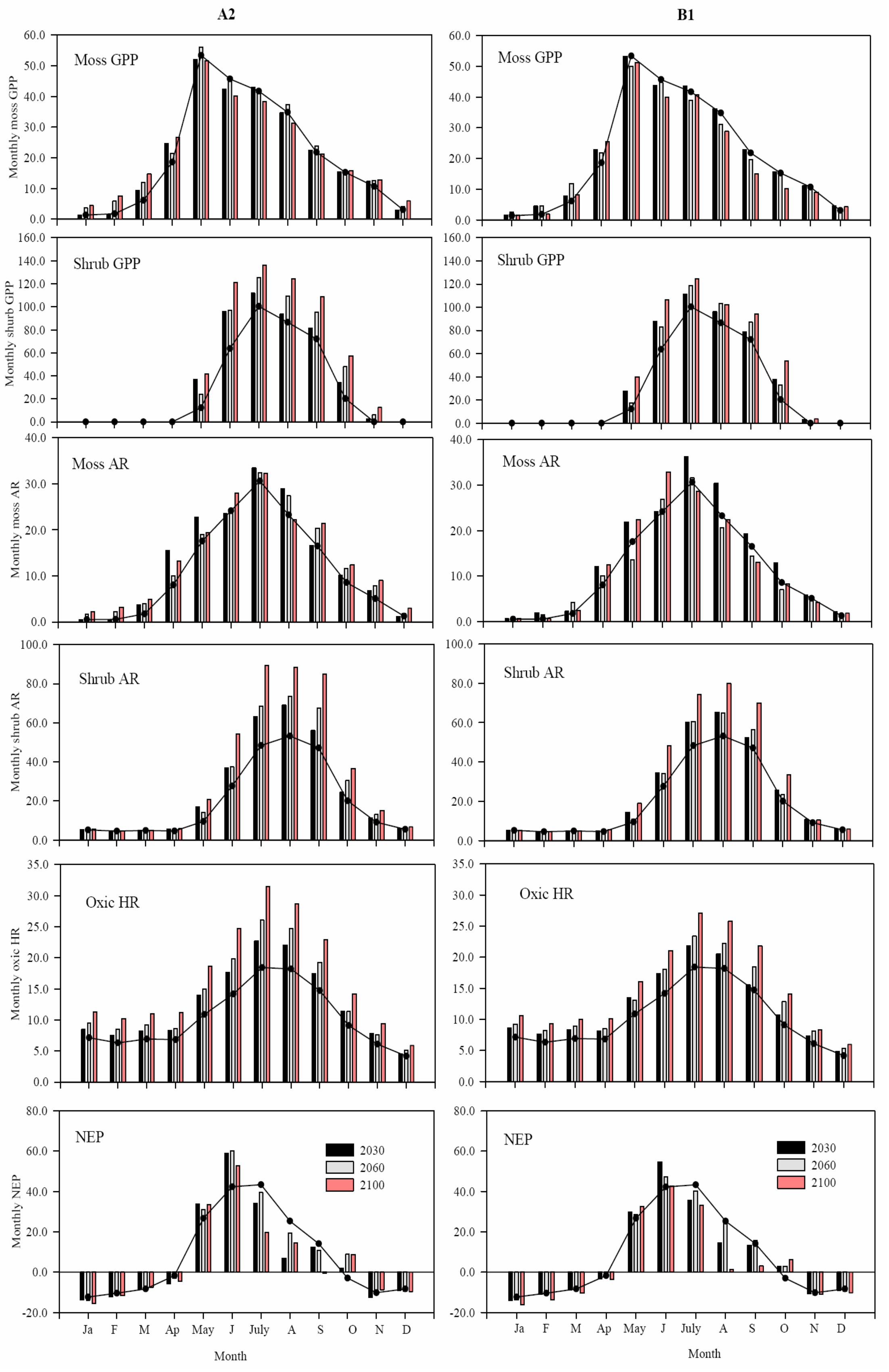


Fig. 6.6: The monthly C fluxes for 2030, 2060 and 2100 at MB. Left column is for A2 and right for B1.

From the top to bottom are moss GPP, shrub GPP, moss AR, shrub 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. (See next page)


A2
B1
Moss GPP
Monthly moss GPP
Shrub GPP
Monthly shurb GPP
Moss AR
Monthly moss AR
Shrub AR
Monthly shrub AR
Oxic HR
Monthly oxic HR
NEP
Monthly NEP
2030
2060
2100
Ja
F
M
Ap
May
J
July
A
S
O
N
D
Month

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. 6.4). For all the scenarios except Commit, TER was enhanced by 195-291 g C m^{-2} yr^{-1} up to 2100. For Commit, TER experienced only a slight variation over time up to 2100. Among the components composing TER (Fig. 6.5), *i.e.* autotrophic respiration (AR), oxic and anoxic decomposition (oxic HR and anoxic HR) (TER =AR+oxic HR+anoxic HR), the largest increase was in AR (~140-210 g C m^{-2} yr^{-1}), followed by oxic HR (~60-77 g C m^{-2} yr^{-1}). And anoxic HR increased only slightly by 1-3 g C m^{-2} yr^{-1} (Fig. 6.5).

NEP, *i.e* GPP-TER, decreased in all scenarios by 2100 because the changes in TER > the changes in GPP. NEP decreased by ~16-45 g C m^{-2} yr^{-1} by 2100 (Fig. 6.4), but in all scenarios the bog remained C sink. The changes in NEP were not linear over time. For example, 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. 6.4).

Climate change did not significantly modify the seasonal patterns of CO_2 exchange for mosses and shrubs up to 2100 at MB, but did alter their magnitudes, particularly in the spring for mosses and in the summer for shrubs (Fig. 6.6). Moss GPP increased significantly in the spring and early summer while it decreased slightly in most of the growing season and did not show significant change in the autumn and winter. But moss AR did show a slight increase in all seasons. Both shrub GPP and AR increased significantly in the growing season, but the magnitude of increase in shrub AR was larger than that in shrub GPP (Fig. 6.6). Therefore, shrub NPP (GPP-AR) decreased. Oxic HR increased in all seasons, but the increase in the growing season was significant larger than other seasons. Accordingly, the changes in NEP also mainly occurred in the growing season (Fig. 6.6: bottom boxes). In 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.

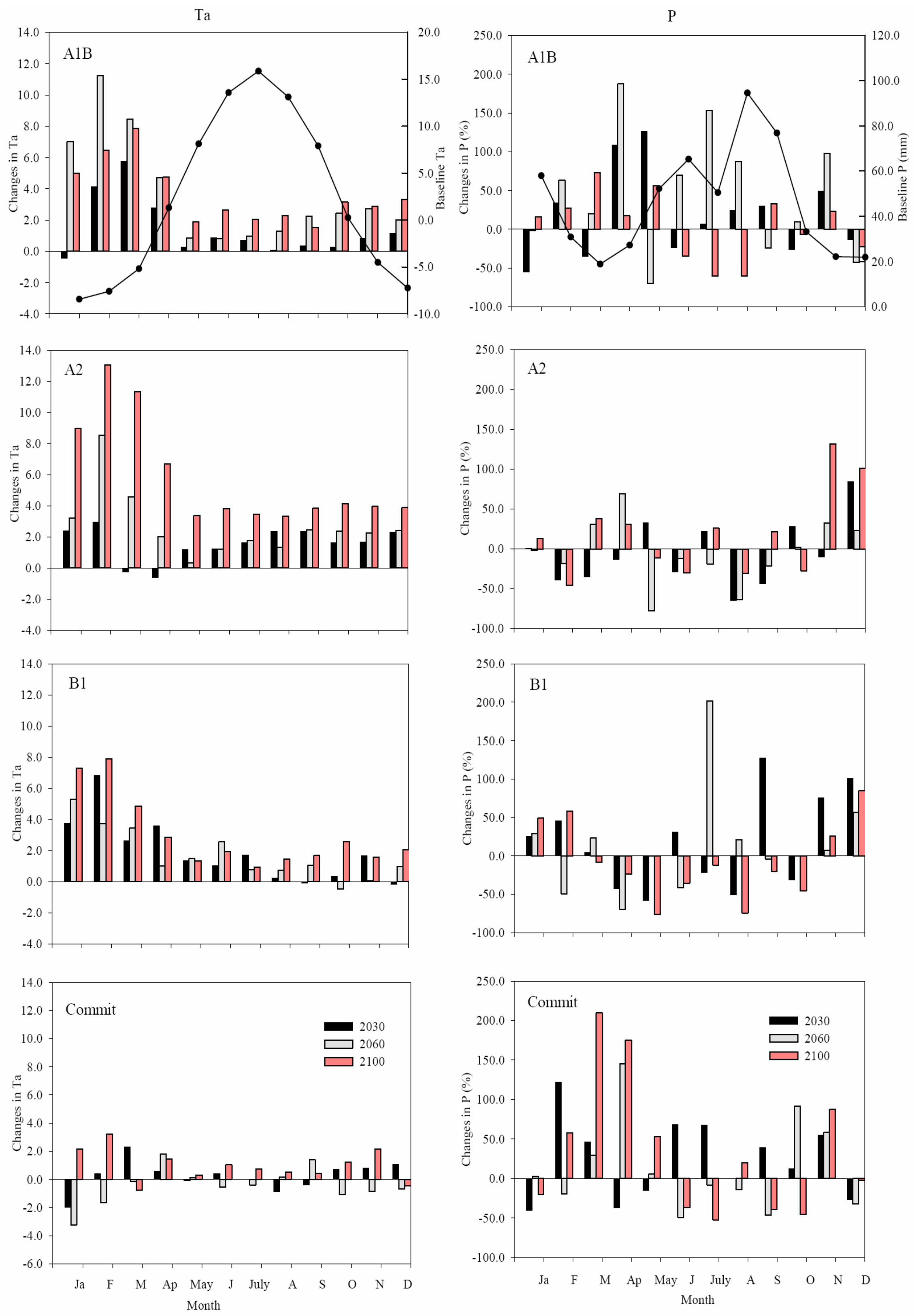
6.3.2 Degero Stormyr fen (DS)

6.3.2.1 Environmental variables

For all scenarios except Commit, Ta rose continuously up to 2100 though the magnitude of change varied among scenarios (Fig. 6.2: right column). The increase in Ta between periods were larger than those projected for MB (Fig. 6.2: left column) because DS is nearly 20°farther north than MB. Temperature increased in all months in all scenarios, except Commit (Fig. 6.7: left column), but the increases were much larger in the spring than other seasons. The maximum increase in temperature in the spring was ~ 13 ℃ (A2 scenario in 2100) but most of the temperature increases in other seasons were < 4 ℃ for DS.

Fig.6.7: The monthly changes in CGCM3.0 simulated Ta (℃) and P (%) for 2030, 2060 and 2100 relative to the 40 years’ average from 1961-2000 at DS.

Left is for Ta and right for P. From top to bottom are for A1B, A2, B1 and Commit respectively. The baseline Ta and P is inserted in the top left and right box respectively. (See next page)


Ta
P
A1B
A2
B1
Commit
Changes in Ta
Baseline Ta
Changes in P (%)
Baseline P (mm)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
20.0
15.0
10.0
5.0
-5.0
-10.0
250.0
200.0
150.0
100.0
50.0
-50.0
-100.0
120.0
100.0
80.0
60.0
40.0
20.0
2030
2060
2100
Ja
F
M
Ap
May
J
July
A
S
O
N
D
Month

The annual changes in P were different for DS than MB (Fig. 6.2). The annual P did not change consistently among the scenarios. The annual P increased slightly up to 2100 for A2 and Commit, but for A1B and B1 after increasing slightly through 2030 to 2060 it then decreased to 2100 (Fig. 6.2: right column). Changes in monthly P were quite variable but the largest increases occurred in winter and spring, except a slight increase in January P in A1B and B1, and most of the decreases occurred during the growing season (Fig. 6.7: right column).

Changes in soilT did not show a consistently increasing or decreasing trend over time (Fig. 6.2: right column). Interestingly, except A2, where soilT decreased first and then increased by ~1 ℃, for all other scenarios soilT increased slightly by < 0.5 ℃ first and then decreased by < 0.5 ℃ (Fig. 6.2: right column), though Ta rose for all scenarios except Commit (Fig. 6.2: right column and 6.7: left column). Also in contrast to MB, at DS the drop of water table was very much larger in A1B and A2 scenarios - 50 and 70 cm respectively by 2100 (Fig. 6.2: right column). With B1 scenario the changes in water table was similar to that of MB and there was only a marginal change with Commit scenario.

Changes in the length of growing period (defined by the number of days with Ta > 0.0 ℃ for moss and > 4.0 ℃ for vascular plants) for moss and vascular plant at DS were not significantly different than those at MB (Table 6.5 a,b), though the changes in Ta at DS, in particular the monthly changes in Ta, were significantly different than those at MB (Fig. 6.3: left column and Fig. 6.7: left column). Similar to MB, for all scenarios except Commit, the length of growing period increased up to 2100 (Table 6.5 b). The increase for A2 (>85 days) was much larger than that for A1B (~45-65 days) and B1 (~40-53 days). Under Commit, there was only a marginal variation over time.

6.3.2.2 CO_2 exchanges

Based on the large changes in the water table with A1B and A2 scenario, the GPP of DS reduced ~180 g C m^{-2} yr^{-1} by 2100 (Fig. 6.8). 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.

There were only modest increases in TER (Fig. 6.8). Again 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 only experienced a slight increase of ~20 g C m^{-2} yr^{-1} by 2100. Further, the temporal trend of changes in TER was not consistent over time among scenarios. Oxic HR was enhanced for all scenarios up to 2100 (Fig. 6.9), but the increase in oxic HR for A1B and A2, by >100 g C m^{-2} yr^{-1} , was much larger than that for other scenarios, by <50 g C m^{-2} yr^{-1}. Both anoxic HR and AR experienced both increase and decrease, depending on the scenario of interest, hence when an increase in TER occurs it is attributable to an increase in oxic HR.

Fig. 6.8: The CLASS3W-MWM simulated CO_2 fluxes (GPP, TER and NEP) at DS for Baseline, 2030, 2060 and 2100 for A1B, A2, B1 and Commit respectively.

From top to bottom are for GPP, TER and NEP respectively. The unit is g C m^{-2} yr^{-1}.

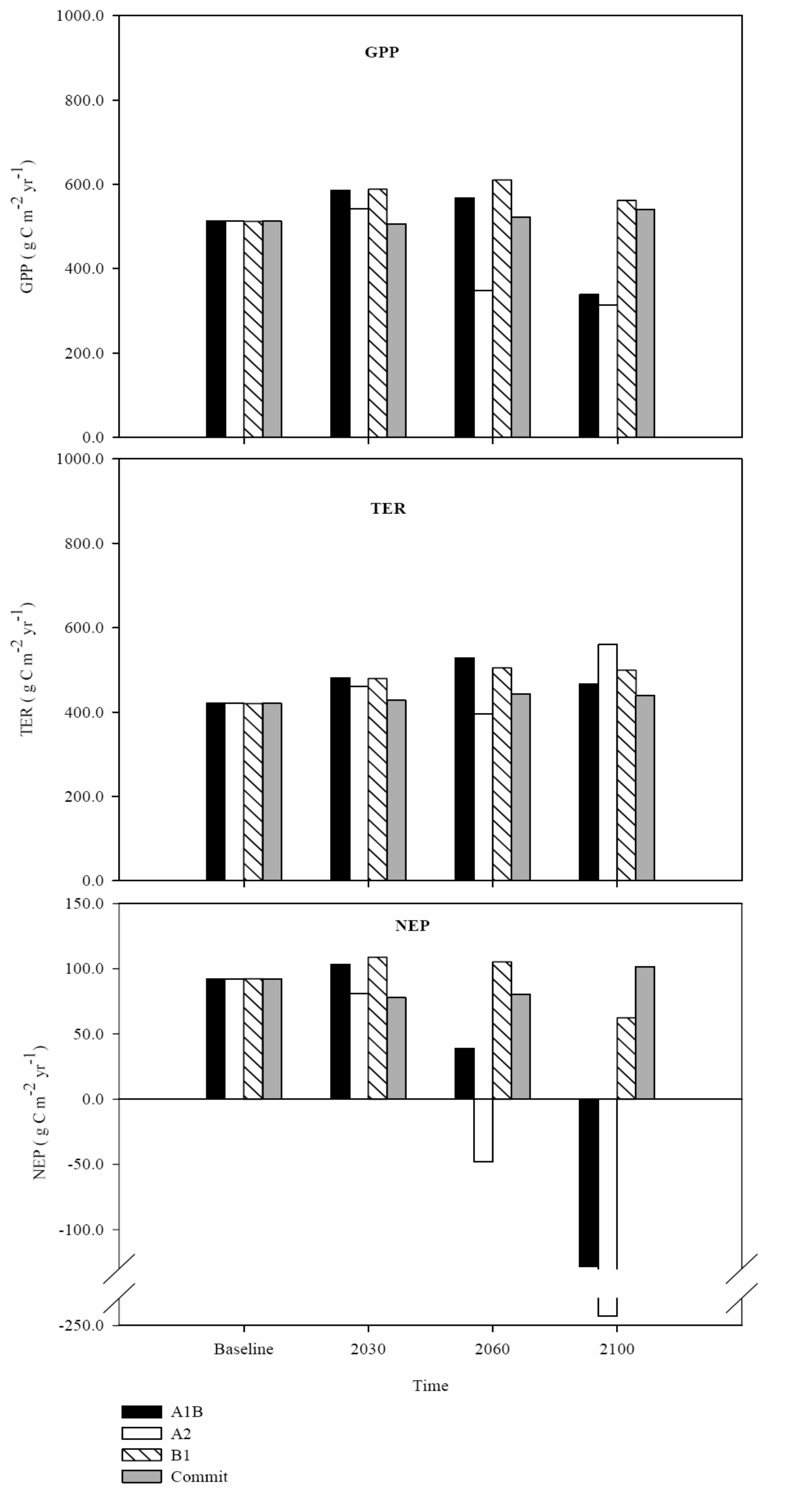


Fig. 6.9: The CLASS3W-MWM simulated components of TER at DS for Baseline, 2030, 2060 and 2100 for A1B, A2, B1 and Commit respectively. The unit is g C m^{-2} yr^{-1}.

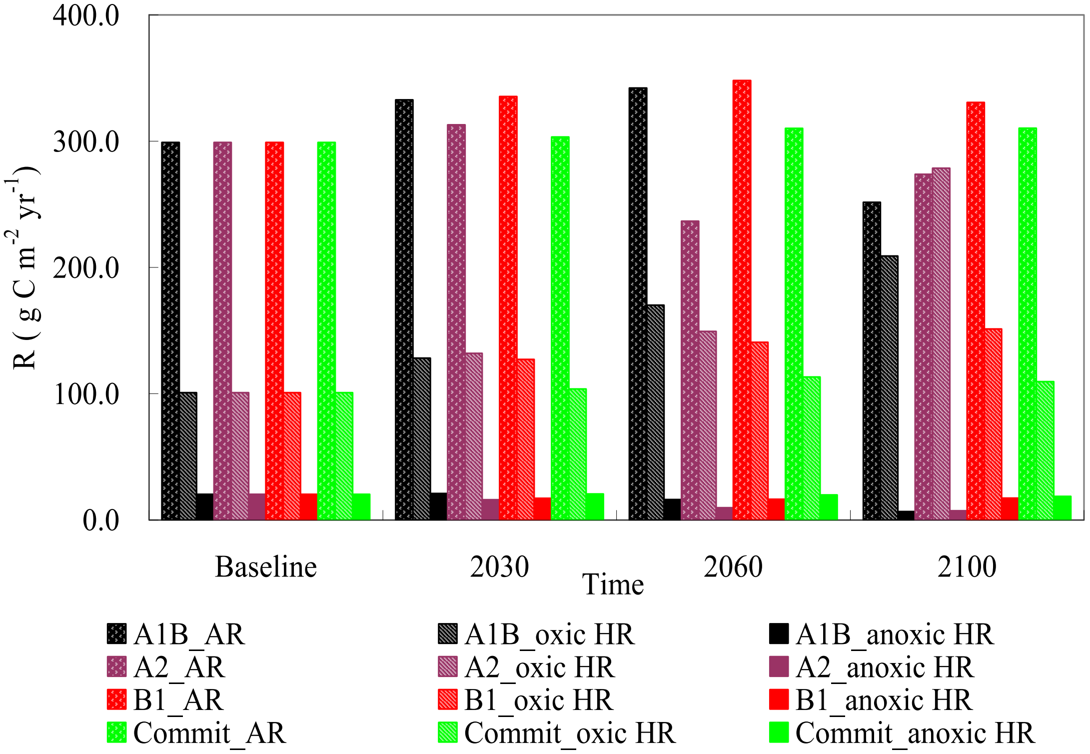
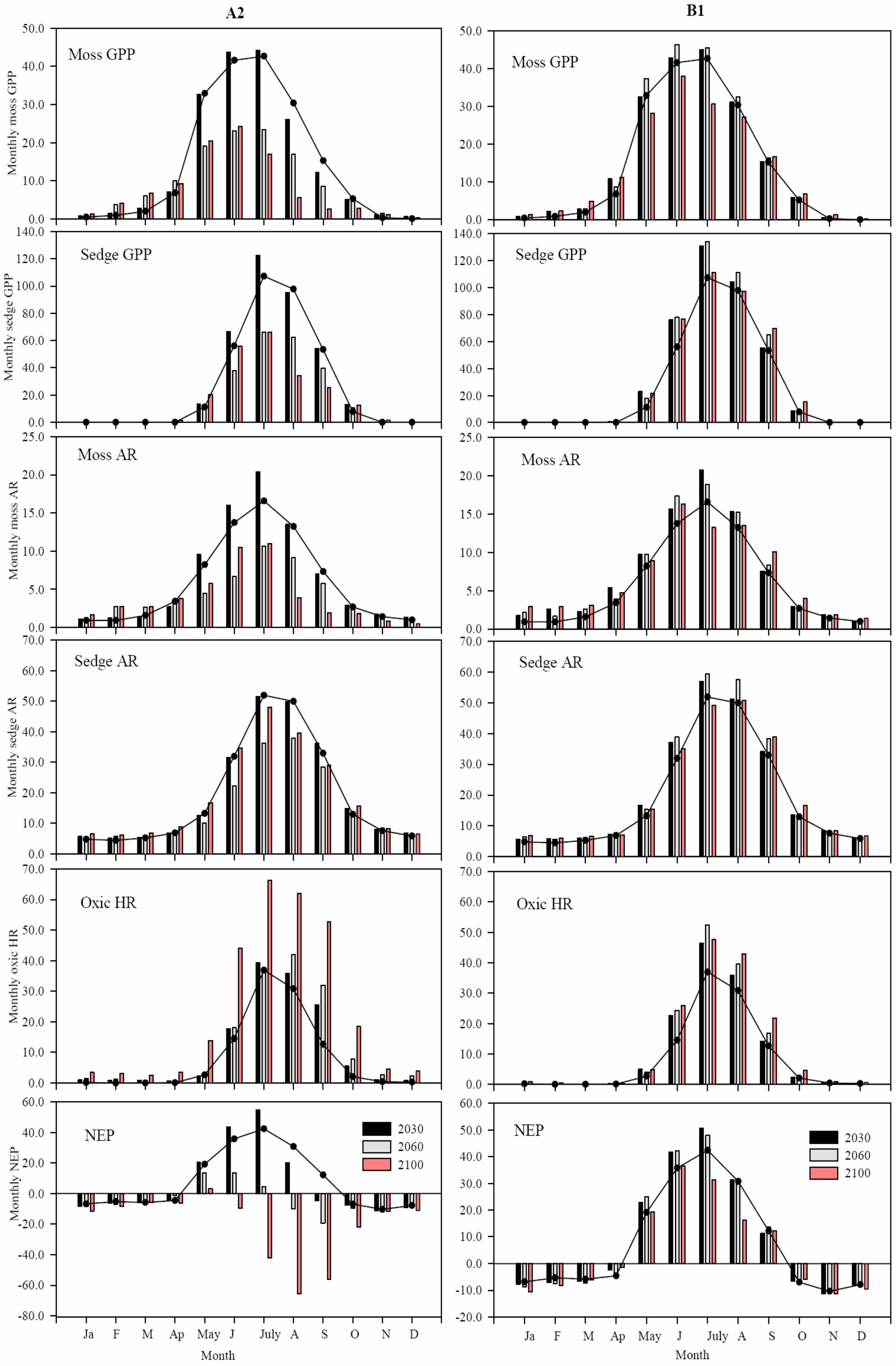


Fig. 6.10: The monthly C fluxes for 2030, 2060 and 2100 at DS. Left column is for A2 and right for B1.

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. (See next page)



A2
B1
Moss GPP
Monthly moss GPP
50.0
40.0
30.0
20.0
10.0
0.0
Sedge GPP
Monthly sedge GPP
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Moss AR
Monthly moss AR
25.0
20.0
15.0
10.0
5.0
0.0
Sedge AR
Monthly sedge AR
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Oxic HR
Monthly oxic HR
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
NEP
Monthly NEP
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
50.0
30.0
10.0
-10.0
2030
2060
2100
Ja
F
M
Ap
May
J
July
A
S
O
N
D
Month

Due to both decreases in GPP and/or increases in TER, there was a significant decrease in NEP for all the scenarios except Commit. Under Commit, NEP increased slightly (Fig. 6.8). For A1B and A2, DS switched to a C source (Fig. 6.8). For A2 this occurred between 2030 and 2060 and for A1B it occurred after 2060. For B1, NEP remained positive, *i.e.* C uptake.

Similar to MB, climate change did not significantly modify the seasonal patterns of CO_2 fluxes for mosses and sedges up to 2100, but did alter their magnitudes, particularly in the spring and summer for mosses and in the summer for sedges (Fig. 6.10). Both moss GPP and AR increased in the spring up to 2100 and did not show significant changes in the winter for both A2 and B1. For A2, both moss GPP and AR increased slightly up to 2030 and after 2030 decreased dramatically in the growing season. For B1, both moss GPP and AR increased slightly up to 2060 and then decreased slightly in the growing season. 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 in the whole growing season. For B1, both sedge GPP and AR increased slightly up to 2100 in the growing season. Sedge AR did not show significant difference in the non-growing season for both A2 and B1. Oxic HR increased significantly in the growing season for both A2 and B1 up to 2100. As a result of significant decrease in GPP and increase in oxic HR in the growing season, for A2 DS lost C to the atmosphere in the growing season except May by 2100, but DS remained C sinks in early summer before 2060. However, for B1, due to increase in both moss and sedge GPP, in spite of significant increase in oxic HR, DS remained a C sink for the entire growing season up to 2100. For both A2 and B1, NEP did not show significant changes in the non-growing season up to 2100.

6.4 Discussion

6.4.1 Climate change in northern peatlands over the 21st 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), where 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 the climate change may impact the 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 CO_2 (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 CO_2 (Luo *et al.*, 2008). Due to physical constraints and temporal scale no manipulations have examined the concurrence of changes expected with future climate change.

Warmer temperature at high latitudes occurs in all the GCM simulations included in the 4th 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 those for precipitation (IPCC, 2007). The models generally suggest an increase in precipitation at high latitudes (Meehl *et al.*, 2007), though it is not evenly distributed throughout the year and decreases occur during the growing season in some climate simulations. In our study, the growing season decreases in precipitation 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 a very much drier fen in the A1B and A2 scenarios. 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 (Chapter 5), suggesting that peatlands are thermally conservative ecosystems (Charman, 2002).

Moreover, 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 is even more salient farther north, for example DS in this study. However, precipitation does not show a consistent trend among models and SRES emission scenarios (Meehl *et al.*, 2007). The seasonal distribution of precipitation can change. If the decrease in ecosystem moisture and increase in temperature occur during the growing season, it can have a much more significant effect than if they 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 DS fen's more northern location. For MB, the temperature increase in the spring season (from January to April) is slightly larger than other seasons, but it is significantly larger than in other seasons for DS. This spring season warming (particularly for DS) should influence the phenology of vegetation, in particular moss, 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 is extended farther than the vascular plants.

6.4.2 The response of C cycling to climate change in northern peatlands over the 21st century

Our simulations show that NEP decreases for both bogs and fens because the magnitude of increase in TER exceeds that in GPP (Fig. 6.4 and 6.8). 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 done 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). But 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 soil for the bog and fen has similar response to climate change. The oxic HR for 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 conditions which they tend to tolerate and continue to function reasonably normally with respect to a large range of environmental changes, as long as environmental changes are not large enough to impose a stress on the biogeochemical function of vegetation. But fens have a narrow tolerance range and therefore they tend to change much more dramatically for the same range of environmental changes. 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 in the growing season though moss GPP increases in the spring, but shrub photosynthesis is enhanced significantly in the growing season. This is because increases in temperature and the concentration of atmospheric CO_2 have a positive effect on moss production, while the changes in precipitation do not impose an additional constraint on moss water content. Our results are qualitatively agreement with the field manipulations which 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 CO_2 fertilization experiments which found that elevated CO_2 did not have a significant effect on bog ecosystems (Hoosbeek *et al.*, 2001) because of nutrient poor status, although elevated CO_2 increased the height growth of *Sphagnum* moss (Heijmans *et al.*, 2001). However, at present, the CLASS3W-MWM does not incorporate nutrient limitations, so plants respond positively to CO_2 fertilization if there is sufficient moisture.

The combined effects of increases in temperature, concentration of atmospheric CO_2 and 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 (Chapter 3 and 5). 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, though moss GPP increases in the spring. This 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 in the growing season. Once water table depth drops below peat surface by > 40 cm (Chapter 3 and 5), the water stress on vegetation growth increases significantly. 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 (St-Hilaire *et al.*, 2008). Accordingly, the extension or shortening of the growing period responds directly to the changes in temperature, particularly in the spring and autumn. Our results do show that moss GPP for the bog and fen are enhanced in the spring. This indicates that more warming in the spring results in an earlier onset of vegetation production and thus increases in GPP in the spring. Though much larger warming occurs in the spring for DS fen, the increase in moss GPP for DS fen does not show a significant difference than for MB bog. This is because the present-day absolute temperature in DS fen is much lower than that for MB bog and only much larger warming can initiate the moss production in the spring for DS fen. However, the warming is not large enough to initiate the production of vascular plant and thus shrub GPP for MB bog and sedge GPP for DS fen do not show any increase in the spring.

In CLASS3W-MWM, AR is simulated as a function of GPP and temperature (St-Hilaire *et al.*, 2008). 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.*, 2008 and Chapter 3 and 5) and peat temperature affects the decomposition rate (St-Hilaire *et al.*, 2008). Because of increase in peat temperature and water table, oxic HR generally increases, in particular in 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.*, 2008). Therefore, changes in AR and oxic HR generally determine the changes in TER.

Whether peatlands remain C sink or switch to C source is determined by the balance between primary production (GPP) and decomposition (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 results illustrate that changes in GPP determine the direction of C exchange in northern peatlands. Significant increase in GPP in the bog, resulting from warming temperature and elevated CO_2 concentration, cancels out the dramatic increase in soil decomposition and thus the bog remains C sink by 2100, though the strength of C sink is significantly reduced. Contrastingly, the significant decrease in GPP in 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 for the fen. Our study also suggests that only significant increase in GPP can maintain the bog as a sink for the atmospheric C. This 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 21st century, considering CO_2 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, all else being equal, the atmosphere will have more CO_2. However, because peatlands represent a relatively small area, only the extreme A1B and A2 changes in the fen would amount to an appreciable source of atmospheric CO_2. Assuming that northern peatlands are 50% bogs and 50% fens, the A2 scenario would amount to < 32 P g C , equivalent to ~14.5 ppm, to the atmosphere up to 2100. This certainly would be significant. However, all other scenarios would result in < 22 P g C increase of CO_2 to the atmosphere up to 2100. Friedlingstein *et al.* (2006) studied that an extra 50-100 ppm CO_2 would stay in the atmosphere for A2 scenario due to the climate warming feedbacks, although northern peatlands were not considered in their study.

To address the total peatland feedback, a simulation of full C balance, including CO_2 and CH_4 exchange between peatlands and the atmosphere, is required in the context of global simulation under the climate change, 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).

6.4.3 Uncertainties and limitation

This is a first attempt, to the best of our knowledge, to examine the sensitivity of the net ecosystem productivity of northern peatlands to the projected changes in climate over the 21st century. Even though we believe this work represents significant progress, we acknowledge that there are a number of significant uncertainties and limitations with this study.

Firstly, CLASS3W-MWM assumes fixed vegetation. There is no change in plant community structure with changes in environmental variables. However, plant communities in peatlands do change when there are, in particular, significant changes in moisture (Weltzin *et al.*, 2000; Weltzin *et al.*, 2003), especially for 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 longer time framework vegetation succession is from graminoid fens to shrub or tree-dominated plant communities with a lower water table depth and this leads to a greater C accumulation in both soil and plant biomass in northern fens (Weltzin *et al.*, 2000; Weltzin *et al.*, 2003).

Secondly, CLASS3W-MWM is a 1-D model. This indicates that only vertical exchanges in water, energy and C are accounted for. Peatland scale lateral outflow is simulated by CLASS3W-MWM for bogs, 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.*, in press) 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 omission of the horizontal linkage between peatlands and surrounding uplands, especially for water exchange, we cannot simulate the water table depth for a fen properly. It is likely that we overestimated the reduction of water table depth leading to an overestimation of the magnitude of C loss in the fen.

Thirdly, at present CLASS3W-MWM only coupled one-way-*i.e.* the physical variables are passed from CLASS3W to the MWM, but the ecosystem attributes are not passed back to CLASS3W.

Fourthly, no nitrogen (N) cycling is included in this study. 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).

Fifthly, as mentioned in the previous section, to examine the net changes in peatland climate feedbacks methane needs to be also simulated. Ideally the loss of C by dissolved organic carbon (DOC) export should be also added.

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).

Chapter 7 Conclusions and future research

The concentration of greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4) in the atmosphere has been increasing since the industrialization at a much larger rate than pre-industrialization (IPCC, 2007). This continuous increase of GHG in the atmosphere has been recognized to be a main contributor for the future increase in global temperature and changes in precipitation patterns (IPCC, 2007; Meehl *et al.*, 2007). It has been acknowledged that this increase is mainly due to the anthropogenic greenhouse gas emission (IPCC, 2007) resulted from burning of fossil fuels and human-induced land use change (Houghton, 1995; Houghton, 1999). Only about half of the anthropogenic CO_2 stay in the atmosphere and the rest has been absorbed by both ocean and terrestrial ecosystems. However, there is much spatial and temporal variability concerning over how terrestrial ecosystems exchange the C with the atmosphere (Houghton *et al.*, 1998; Schindler, 1999; Schimel *et al.*, 2001; Sarmiento and Gruber, 2002). The first generation of C-coupled climate models have shown that a significant positive feedback exist between terrestrial C cycling and climate change (Cox *et al.*, 2000; Matthews, 2005; Friedlingstein *et al.*, 2006; Denman *et al.*, 2007). There is concern over how the terrestrial ecosystem will respond to projected climate change and whether they will maintain their C function. Moreover, the terrestrial C cycle has been recognized to be one of the main uncertainties in projecting the future climate (Huntingford *et al.*, 2009). This uncertainty is exacerbated due to omission of peatlands (wetlands in general), fire disturbance and nitrogen cycling in the first generation of C-coupled climate model (Friedlingstein *et al.*, 2006; Denman *et al.*, 2007; Limpens *et al.*, 2008; Sokolov *et al.*, 2008; Frolking *et al.*, in press).

Globally, peatlands occupy about 4×10^6 km^2, with northern peatlands estimated to be approximately 3.46×10^6 km^2 or about 87% of the world's peatlands (Gorham, 1991; Joosten and Clarke, 2002; Vitt, 2006). Northern peatlands have stored ~450 Gt C mostly during the Holocene after the last glaciation (Gorham, 1991; Turunen *et al.*, 2001; Turunen *et al.*, 2002; Bridgham *et al.*, 2006), resulting from their bigger NPP than their decomposition. This large storage of organic C is equivalent to about 1/3 of the world terrestrial C and about half mass of the atmospheric C (Schlesinger, 1997; Roulet, 2000). In Chapter 2, it was described that hydrology is a key physical factor to maintain the ecological and biogeochemical function for northern peatlands. Moreover, hydrology and thus biogeochemistry in northern peatlands are tightly linked to climate (Hilbert *et al.*, 2000; Charman, 2002; Yurova *et al.*, 2007; Bridgham *et al.*, 2008; Ise *et al.*, 2008; Breeuwer *et al.*, 2009; Robroek *et al.*, 2009). However, over 80% of world peatlands are located in the high latitude region where the future climate is projected to experience a significant change with a much warmer and possibly drier condition in 21st century (Meehl *et al.*, 2007). Therefore, concern exists over the possibility of northern peatlands becoming significant C sources for the atmosphere under a changed climate (Yu, 2006; Limpens *et al.*, 2008). However, there are many uncertainties in addressing the C responses in northern peatlands to climate change (Moore *et al.*, 1998; Limpens *et al.*, 2008). This thesis has shed some light on this issue and examined the sensitivities of C cycling in northern peatlands to the projected climate change.

The specific objectives of the research presented in this thesis were to develop a model to simulate and characterise the hydrological and biogeochemical processes in northern peatlands and then to examine the responses of C cycling in northern peatlands to the possibly changed climate for the 21st century. A process-based ecosystem model, called McGill Wetland Model (MWM), which was developed for northern peatlands in general, but only previously evaluated on an ombrotrophic bog, was modified to represent the distinct hydrological and biogeochemical processes in a minerotrophic poor fen (Chapter 3). Fens are extensive peatland in the Northern Hemisphere. The modified MWM was then evaluated by comparing the simulated C fluxes with an eddy-covariance measurement of C fluxes at Degero Stormyr (64°11'N, 19°33'E), in Northern Sweden. Bogs possess significant microtopographic differences in the C cycling at a micro-site scale. One has to parameterize an ecosystem model to represent the microtopographic characteristics. In Chapter 4, two types of scaling, flux and parameter upscaling, were examined. Chapter 5 described how the MWM coupled to a land surface climate model, the wetland version of Canadian Land Surface Scheme (CLASS3W) to examine the C cycling in northern peatlands as they might be influenced by climate change. As this coupling now introduces the additional simulation of peatland climate, this coupled model, called CLASS3W-MWM, was evaluated for both an ombrotrophic bog and a minerotrophic poor fen by comparing the modelled C fluxes with the eddy-covariance measurement of C fluxes. The results of the thesis research concluded with the application of the CLASS3W-MWM in the different period, 2030, 2060 and 2100, to do the first quantitative assessment of the sensitivity of C cycling in northern peatlands to the changes in climate expected in the 21st century.

7.1 Significant findings from my thesis research

7.1.1 Further development of MWM

Three modifications were made to the original MWM to characterize the biogeochemical, hydrological processes and vegetation composition of a poor fen: (1) a function describing the impact of soil moisture upon the optimal GPP; (2) a scheme to partition the peat profile into oxic and anoxic C compartment for the one-box decomposition module, based on the "effective root depth" as a function of daily sedge NPP; and (3) a modified function describing the 'fen' moss water dynamics.

The results show that the modified MWM adequately captures the magnitude and direction of the CO_2 fluxes and simulates the seasonal and inter-annual variability well. RMSE for daily NEE is ~0.20 g C m^{-2} d^{-1} and d* between the observed and simulated NEE is ~85%. This research further confirms that hydrology is playing a key role in the biogeochemical processes of minerotrophic poor fen. Moreover, our study agrees that northern peatlands should be subdivided into 2 categories at least, *i.e.* dry (bog) and wet (fen) peatland for examining the C exchanges between peatlands and the atmosphere (Yi *et al.*, 2009;

Baird *et al.*, in press).

7.1.2 The effects of microtopography on the ecosystem-level C cycling in northern peatlands

Constructing a model for peatland ecosystems presents a number of unique challenges, one of which is how to deal with the large variability that occurs at small scales (*i.e.* 1-3m). Microtopography is a common feature of bogs. Flux and parameter upscaling are the two commonly-used approaches to modelling systems. Our results showed that the hummocks and hollows had similar GPP, but there were significant differences in TER. This is due to the difference in the biophysical and hydrological properties in acrotelm between hummocks and hollows. However, despite the differences in individual components on the C exchange between hummocks and hollows, the difference scaled linearly, so there was no significant difference in simulated outputs of GPP, TER and NEE between the flux and the parameter upscaling methods. We conclude that parameter upscaling does not introduce a significant and systematic bias, and the hummock-hollow variability can be modelled adequately using a much more computationally efficient parameter upscaling.

7.1.3 Coupling of MWM with CLASS3W (*i.e.* CLASS3W-MWM)

Peatlands and their C cycling are very sensitive to climate change and variability. To address this issue, we coupled MWM to CLASS3W (Wetland version of Canadian Land Surface Scheme) (referred as CLASS3W-MWM). Our results show that CLASS3W-MWM can capture the magnitude and direction of the contemporary C cycling well for both bogs and fens. Moreover, the seasonal and interannual variability was reproduced reasonably well for both bogs and fens by CLASS3W-MWM. Our sensitivity analysis showed that C cycling for bogs and fens is more sensitive to changes in temperature than precipitation within the range of changes projected in the 21st century. Changes in air temperature (Ta) can switch northern peatlands from the present C sinks to C sources. Changes in precipitation (P) alone, however, did not make northern peatlands switch from C sink to a C source. We found that fens are more sensitive to climate change than bogs. Finally, the sensitivity analysis showed that the combination of changes in Ta, P and increased concentration of atmospheric CO_2 produced different results than any one of the environmental variables on their own. Increases in Ta and reduction in P produced the largest change to a source of C, and this was only partially offset by the increase in productivity resulted from increased concentration of atmospheric CO_2.

7.1.4 Sensitivity of C cycling in northern peatlands to climate change

CLASS3W-MWM was used to examine the changes in the C function of biogeochemistry of northern peatlands with a projected warmer and generally drier climate with respect to a number of future climate scenarios. The study peatlands we selected were an ombrotrophic bog in eastern Canada and a minerotrophic poor fen in northern Sweden. Four IPCC climate change scenarios were used, A1B, A2, B1 and Commit, and 3 time slices, 2030, 2060 and 2100, were chosen for analysis. We found that the bog had a significantly different response to climate change than the fen. Specifically, the fen was much more sensitive to climate change than the bog. GPP at Mer Bleue increased by 151-262 g C m-^{2} yr^{-1} by 2100 for all scenarios except Commit, while GPP at Degero Stormyr decreased by ~180 g C m-^{2} yr^{-1} for A1B and A2, and increased slightly by 30-50 g C m-^{2} yr^{-1} for the B1 and Commit. TER for both peatlands increased: 195-291 g C m-^{2} yr^{-1} for the bog and 50-140 g C m-^{2} yr^{-1} for the poor fen by 2100 for all scenarios except Commit. NEP decreased in both peatlands, because the magnitude of the increase for TER exceeded that of GPP. Mer Bleue bog became a smaller C sink up to 2100, for all scenarios, but Degero Stormyr switched from a C sink to a source in the A1B and A2 scenario. From our preliminary analyses it appears that fens, while being generally wetter peatlands than bogs, are more sensitive to the range of changes expected over the 21st century.

7.2 Major contributions of this thesis

Through the research presented in this thesis, I have made the following significant original contributions in the field of terrestrial ecosystem ecology, specifically, in the field of peatland (or wetland in general) biogeochemical cycling modelling.

(1) I have further developed and evaluated a process-based model, the McGill Wetland Model (MWM), to simulate the vertical C cycling between a fen peatland and the atmosphere. My primary contribution was to adapt and

parameterize the MWM to simulate the C balance of northern “fen” type peatlands.

(2) I have examined the effects of microtopography in a bog peatland on the ecosystem-level C cycling and how the micro-scale variation in northern peatlands can be characterized in the simulation of an ecosystem-scale C cycling. My major contribution was to find that the microtopography, represented by the variation in hydrology, soil climate, biogeochemistry and vegetation composition, would not be necessary to model explicitly in an ecosystem-level C cycling simulation, but can be simulated implicitly by a spatial-average ensemble of microtopography - hummocks and hollows (parameter upscaling). This will make regional scale biogeochemical simulations of peatland interaction with climate much easier and computationally efficient. Moreover, my research was the first one to compare and examine how efficient and different flux and parameter upscaling would be to characterize the spatial heterogeneity in an ecosystem-level simulation.

(3) I have coupled MWM and a wetland version of Canadian Land Surface Scheme (referred as CLASS3W-MWM) so I could examine the sensitivity of the peatland C cycling to the projected climate change. CLASS3W-MWM was successfully evaluated in both a bog and a poor fen peatland. The sensitivity analysis using the CLASS3W-MWM showed that (a) changes in temperature resulted in large changes in C dynamics within the range of expected changes in the 21st century, (b) fens proved to be more sensitive to changes than bogs, and (c)

the sensitivity of the combination of temperature, precipitation and doubled CO_2 concentration is much different than the sensitivity of peatlands to each environmental variable on their own.

(4) I have carried out a first-order experiment on how the C exchange between northern peatlands and the atmosphere might change over the 21st century for several climate change scenarios. To the best of my knowledge, this is the first research to integrate the effects of changes in air temperature, precipitation and atmospheric CO_2 concentration on the C cycling in northern peatlands. My major contribution was to find that fen peatlands, while being generally wetter peatlands than bogs, are more sensitive to the range of climate change expected over the 21st century, and they could switch from a present day C sink to a C source under the IPCC A1B and A2 scenario. Bogs remain a C sink but with a much smaller uptake by 2100 in all four climate scenarios. This research suggests that some northern peatlands could experience a dramatic change in C cycling due to climate change, while other may not.

I can calculate how much the changes in C cycling in northern peatlands might be for the four chosen climate scenarios over the 21st century by making the following assumptions (Table 7.1): (a) half of the northern peatlands are bogs (1.73×10^6 km^2) and the other half are fens (1.73×10^6 km^2); (b) the two peatlands presented in this thesis are representative of the "mean" peatland of each type. More CO_2 will stay in the atmosphere due to reduction in C uptakes or even a C source in northern peatlands for all four climate scenarios by 2100 (Table 7.1).

For example, for A2, ~0.633 P g more C will stay in the atmosphere compared to the present time. If it is assumed that linear changes have been taking place from 2001-2100, northern peatlands will reduce their efficiency to absorb C by ~31.65 Gt C for A2 scenario (Table 7.1). This will result in an additional increase of the atmospheric CO_2 concentration by 14.4 ppm. Friedlingstein *et al.* (2006) found that additional 50-100 ppm CO_2 would stay in the atmosphere for A2 scenario due to the positive climate change feedback. But northern peatlands were not considered in their study.

Table 7.1: The changes in CO_2 exchange between northern peatlands and the atmosphere over the 21st century for the four climate scenarios relative to the present day baseline.

Note: positive means that northern peatlands will uptake more CO_2 from the atmosphere relative to the baseline, while negative means that more CO_2 will stay in the atmosphere relative to the baseline. The unit is P g C yr^{-1} (1 P g C=1×10^{15} g C). The value for baseline represents the present time CO_2 uptake from the atmosphere.

*: Integration over the 21st century for how much northern peatlands will reduce the efficiency of C uptake. Unit: P g C (or G t C).

	A1B	A2	B1	Commit
Baseline	***0.328***	***0.328***	***0.328***	***0.328***
2030	-0.020	-0.038	0.023	-0.079
2060	-0.098	-0.211	0.037	-0.062
2100	-0.444	-0.633	-0.127	-0.012
Integration over the 21st century *	22.2	31.65	6.35	0.6

7.3 Future research

This thesis mainly focused on the further development of MWM for the simulation of vertical CO_2 exchange between peatlands and the atmosphere and a first-order experiment on the sensitivity of C cycling in northern peatlands to the projected climate change for the 21st century. Except vertical CO_2 exchange, methane (CH_4) is another important vertical C exchange component in northern patlands (Nilsson *et al.*, 2001; Christensen *et al.*, 2004; Roulet *et al.*, 2007; Nilsson *et al.*, 2008; Baird *et al.*, in press). To fully examine the C balance for northern peatlands, the MWM needs to be further developed to include all the relevant C exchange components, such as CH_4 and lateral dissolved organic C (DOC). Except the further development and improvement of MWM, this coupled CLASS3W-MWM needs to be implemented at a regional and/or global scale to examine the role of northern peatlands in the global C budget under the changed climate. Moreover, simulation needs to extend to the C-rich arctic and sub-arctic area where the soil is underlain with either continuous or discontinuous permafrost, and large reservoir of C, about 700-950 Pg C, is contained in its top 1-25 meters (Walter *et al.*, 2006; Walter *et al.*, 2007; Schuur *et al.*, 2008; Schuur *et al.*, 2009). This storage of C, which has been locked in either continuous or discontinuous permafrost, should be very sensitive to climate change, because climate change with warming temperature will result in the degradation of permafrost and therefore the previous inactive C will turn into relatively active C (Walter *et al.*, 2006; Walter *et al.*, 2007; Schuur *et al.*, 2008; Schuur *et al.*, 2009).

7.3.1 Further assessment and development of MWM

(1) MWM needs to be evaluated on more peatland sites, where continuous measurements are available. Moreover, MWM should be assessed for simulating

the sensitivity of C cycling to climate change by comparing to the results from manipulative experiments. For example, MWM can be configured at a similar way to the manipulative experiments, such as changes in temperature and CO_2 concentration.

(2) CH_4 needs to be included in MWM to account for the complete C balance and examine the overall radiative forcing for northern peatlands, because methane, in the short term, is a more radiatively potent gas than CO_2 and northern peatlands normally function as CO_2 sinks and CH_4 sources (Smith *et al.*, 2004; Frolking *et al.*, 2006; Frolking and Roulet, 2007). Though CH_4 is only small proportion of total C balance for a bog peatland (Roulet *et al.*, 2007; Limpens *et al.*, 2008), it could be a relatively large C component for a fen peatland (Nilsson *et al.*, 2001; Limpens *et al.*, 2008; Nilsson *et al.*, 2008). For example, CH_4 can be equivalent to around 20% of the net annual C balance for a fen peatland in northern Sweden (Nilsson *et al.*, 2001; Nilsson *et al.*, 2008). Modelling exercise has shown that the simulations with doubling CO_2 can result in an increase in annual average wetland CH_4 emissions from 156 to 277 Tg yr^{-1}, a rise of ~78% (Shindell *et al.*, 2004), of which northern wetlands at the northern high latitude could account for an annual average CH_4 emission from 24 to 66 Tg yr^{-1} .

(3) Dynamic vegetation needs to be characterized in MWM to capture the dynamics of peatland ecosystem with respect to climate change. Incorporation of dynamic vegetation is very important to capture a better representation of the response of C cycling in northern peatlands with respect to climate change (St-

Hilaire *et al.*, 2008; Balshi *et al.*, 2009). Under a warmer and drier (or wetter) climate, the current vegetation composition and vegetation morphology is not likely to remain the same (Weltzin *et al.*, 2000; Weltzin *et al.*, 2003; Strack *et al.*, 2004). Competition between mosses and vascular vegetation in northern peatlands will be modified (Breeuwer *et al.*, 2008a; Breeuwer *et al.*, 2009). It has been observed that a vegetation succession from a graminoid fen to a shrub or tree-dominated plant community with a lower water table depth may lead to greater C accumulation in both soil and plant biomass in northern fens (Weltzin *et al.*, 2000; Weltzin *et al.*, 2003). However, this increase in soil-C accumulation rate in peatlands with warmer/wetter conditions may be more than offset by higher CH_4 emissions (Bridgham *et al.*, 2006). Moreover, it has been observed that under the warmer climate the enhanced growth of vascular plants can overwhelm the increased C loss from the thawing of permafrost and maintain the C sink function in high latitude permafrost peatlands (Schuur *et al.*, 2009). Finally, the types of vegetation are key controllers to the CH_4 transport and production (Bubier *et al.*, 1995).

7.3.2 Regional/global simulation for C cycling in northern peatlands

This thesis research represents two points for northern peatlands. To fully assess what is the role of northern peatlands in global C cycling, spatial dynamics of C cycling, and the sensitivity of C storage in northern peatlands with respect to the projected climate change, this coupled surface climate and C cycling model, *i.e.* CLASS3W-MWM, should be implemented at a global or regional scale in a spatial explicit manner. Several challenges, however, emerge with the global/regional scale simulation. (1) A spatial hydrological interaction between peatlands, especially fen peatlands, and upland ecosystems and local subsurface hydrological settings would be needed (Limpens *et al.*, 2008; Frolking *et al.*, in press). (2) A global classification of bog and fen peatland is required for the global simulation of peatland C cycling, because bogs and fens have significantly different ecological, biogeochemical and hydrological processes with each other (Chapter 3, 5 and 6) (Bridgham *et al.*, 2008). (3) A global dataset for peatland basal age is needed to initiate the peatland profile so that the oxic and anoxic decomposition in peatland soil can be implemented and the present day C exchange rate is based on the historical development of one specific peatland profile (Yi *et al.*, 2009; Baird *et al.*, in press).

7.3.3 Issues on permafrost peatlands in northern hemisphere

Eighty seven percent of the world's peatlands are distributed in the boreal and subarctic area, of which about 50% is underlain by either continuous or discontinuous permafrost (Vitt, 2006). Northern peatlands are estimated to store up to 450 Pg soil organic C (Gorham, 1991; Turunen *et al.*, 2001; Turunen *et al.*, 2002), of which about half (277 Pg C) is contained in permafrost peatlands (Schuur *et al.*, 2008). The permafrost region has been projected to experience thawing and a deepening of the active layer (Schuur *et al.*, 2008). This will result in a significant change in the C exchanges between permafrost peatlands and the atmosphere (Christensen *et al.*, 2004; Malmer *et al.*, 2005; Schuur *et al.*, 2008;

Schuur *et al.*, 2009; Yi *et al.*, 2009). Several physical and ecological aspects of permafrost ecosystem can be altered by climate change, such as thawing permafrost (or deepening of the active layer), extension of growing season, enhancement of plant growth rates, changes in species composition and ecosystem energy exchange (Christensen *et al.*, 2004; Schuur *et al.*, 2008; Schuur *et al.*, 2009; Yi *et al.*, 2009). It has been shown that the net effect of widespread permafrost degradation will be a positive feedback to a warming climate (Schuur *et al.*, 2008; Schuur *et al.*, 2009). The biogeochemical processes and their changes with respect to climate change, however, have not been well documented. The following key aspects need to be examined for studying the C cycling in permafrost peatlands: (1) the size of the organic C pool in permafrost peatlands; (2) spatial distribution of this organic C pool in permafrost peatlands; (3) changes in hydrological and thermal regimes with respect to climate change; (4) the coupling of hydrological and thermal regimes to the C cycling in permafrost peatlands; (5) the conversion of inactive C pool (frozen C pool) to active C pool (active decomposition and diffusion) under the changing climate; (6) vegetation dynamics in permafrost peatlands with respect to climate change.

Bibliography

Alexandersson, H., Karlstro¨m, C. and Larsson-Mccann, S., 1991. Temperature and precipitation in Sweden 1961 - 1990 reference normals, METEOROLOGI 81/1991. Norrko¨ping., Inst., S. M. a. H.

Almquist-Jacobson, H. and Foster, D., 1995. Toward an integrated model for raised-bog development: theory and field evidence. Ecology, 76:2503-2516.

Anderson, M. C., Kustas, W. P. and Norman, J. M., 2003. Upscaling and downscaling - A regional view of the soil-plant-atmosphere continuum. Agronomy Journal, 95(6):1408-1423.

Arain, M. A., Burke, E. J., Yang, Z. L*., et al.*, 1999. Implementing surface parameter aggregation rules in the CCM3 global climate model: regional responses at the land surface. Hydrology and Earth System Sciences, 3(4):463-476.

Arora, V. K., 2003. Simulating energy and carbon fluxes over winter wheat using coupled land surface and terrestrial ecosystem models. Agr. Forest Meteorol., 118:21-47.

Arora, V. K. and Boer, G. J., 2003. A representation of variable root distribution in dynamic vegetation models. Earth Interactions, 7(6):19.

Auer, V., 1930. Peat bogs in southeastern Canada, Canada. Department of Mines, Ottawa, Ottawa, 32 p.

Baird, A. J., Belyea, L. R. and Morris, P. J., in press. Upscaling peatland-atmosphere fluxes of carbon gases: small-scale heterogeneity in process rates and the pifalls of 'bucket-and-slab' models. In: Baird, A. J., Belyea, L. R., Comas, X*., et al.* (Editor), AGU monograph: Northern peatlands and carbon cycling. AGU.

Ball, J. T., Woodrow, I. E. and Berry, J. A., 1987. A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions. In: Biggens, J. (Editor), Progress in Photosynthesis Research. Martinus Nijhoff, Dordrecht, 221-224.

Balshi, M. S., Mcguire, A. D., Duffy, P.*, et al.*, 2009. Vulnerability of carbon storage in North American boreal forests to wildfires during the 21st century. Global Change Biology, doi:10.1111/j.1365-2486.2009.01877.x.

Basiliko, N., Moore, T. R., Jeannotte, R.*, et al.*, 2006. Nutrient Input and Carbon and Microbial Dynamics in an Ombrotrophic Bog. Geomicrobiology Journal, 23:531-543.

Bauer, I. E., 2004. Modelling effects of litter quality and environment on peat accumulation over different time-scales. Journal of Ecology, 92(4):661-674.

Belyea, L. and Clymo, R., 2001. Feedback control of the rate of peat formation. Proc. Roy. Soc. Lond. B. Bio., 268:1315-1321.

Belyea, L. R. and Baird, A. J., 2006. Beyond "the limits to peat bog growth": cross-scale feedback in peatland development. Ecological Monographs, 76(3):299-322.

Belyea, L. R. and Malmer, N., 2004. Carbon sequestration in peatland: patterns and mechanisms of response to climate change. Global Change Biology, 10(7):1043-1052.

Blackford, J., 2000. Palaeoclimatic records from peat bogs. Trends Ecol. Evol., 15:193-198.

Blodau, C., 2002. Carbon cycling in peatlands - A review of processes and controls. Environmental Review, 10:111-134.

Blodau, C., Roulet, N. T., Heitmann, T.*, et al.*, 2007. Belowground carbon turnover in a temperate ombrotrophic bog. Global Biogeochemical Cycles, 21(GB1021), doi:10.1029/2005GB002659.

Blyth, E. M., Finch, J., Robinson, M.*, et al.*, 2004. Can soil moisture be mapped onto the terrain? Hydrology and Earth System Sciences, 8(5):923-930.

Bragazza, L., Freeman, C., Jones, T.*, et al.*, 2006. Atmospheric nitrogen deposition promotes carbon loss from peat bogs. Proceedings of the National Academy of Sciences, 103(51):19386-19389, doi:10.1073/pnas.0606629104.

Breeuwer, A., Heijmans, M. M. P. D., Gleichman, M., *et al.*, 2009. Response of *Sphagnum* species mixtures to increased temperature and nitrogen availability. Plant Ecol., doi:10.1007/s11258-009-9571-x.

Breeuwer, A., Heijmans, M. M. P. D., Robroek, B. J. M., *et al.*, 2008a. The effect of temperature on growth and competition between *Sphagnum* species. Oecologia, 156:155-167, doi:10.1007/s00442-008-0963-8.

Breeuwer, A., Heijmans, M. M. P. D., Robroek, B. J. M., *et al.*, 2008b. The effect of increased temperature and nitrogen deposition on decomposition in bogs. Oikos, 117:1258-1268, doi: 10.1111/j.2008.0030-1299.16518.x.

Bridgham, S., Johnston, C., Pastor, J., *et al.*, 1995a. Potential feedbacks of northern wetlands on climate change. BioScience, 45:262-274.

Bridgham, S., Pastor, J., McClaugherty, C., *et al.*, 1995b. Nutrient-use efficiency: a litterfall index, a model, and a test along a nutrient-availability gradient in North Carolina peatlands. American Naturalist, 145(1):1-21.

Bridgham, S., Pastor, J., Janssens, J., *et al.*, 1996. Multiple limiting gradients in peatlands: A call for a new paradigm. Wetlands, 16(1):45-65.

Bridgham, S. and Richardson, C., 2003. Endogenous versus exogenous nutrient control over decomposition and mineralization in North Carolina peatlands. Biogeochemistry, 65:151-178.

Bridgham, S. D., Megonigal, J. P., Keller, J. K., *et al.*, 2006. The carbon balance of North American wetlands. Wetlands, 26:889-916.

Bridgham, S. D., Pastor, J., Dewey, B., *et al.*, 2008. Rapid carbon response of peatlands to climate change. Ecology, 89(11):3041-3048, doi:10.1890/08-0279.1.

Bridgham, S. D. and Richardson, C. J., 1992. Mechanisms Controlling Soil Respiration (CO_2 and CH_4) in Southern Peatlands. Soil Biology & Biochemistry, 24(11):1089-1099.

Bridgham, S. D., Updegraff, K. and Pastor, J., 1998. Carbon, nitrogen, and phosphorus mineralization in northern wetlands. Ecology, 79:1545-1561.

Bubier, J., Bhatia, G., Moore, T., *et al.*, 2003a. Spatial and temporal variability in growing-season net ecosystem carbon dioxide exchange at a large peatland in Ontario, Canada. Ecosystems, 6:353-367.

Bubier, J., Linder, E., Crill, P., *et al.*, 2003b. Peatland responses to varying interannual moisture conditions as measured by automatic CO_2 chambers. Global Biogeochemical Cycles, 17(2), doi:10.1029/2002GB001946.

Bubier, J., Moore, T. R. and Crosby, G., 2006. Fine-scale vegetation distribution in a cool temperate peatland. Canadian Journal of Botany, 82:1292-1313.

Bubier, J. L., Moore, T. R. and Juggins, S., 1995. Predicting Methane Emission from Bryophyte Distribution in Northern Canadian Peatlands. Ecology, 76(3):677-693.

Bubier, J. L., Moore, T. R. and Roulet, N. T., 1993. Methane emissions from wetlands in the Midboreal region of northern Ontario, Canada. Ecology, 74(8):2240-2254.

Campbell, J. D., 1974. A simple method for determining unsaturated conductivity from moisture retention data. Soil Science, 117:311-314.

Chapin, C. T., Bridgham, S. D. and Pastor, J., 2004. pH and nutrient effects on above-ground net primary production in a Minnesota, USA bog and fen. Wetlands, 24:186-201.

Chapin III, F. S., Matson, P. A. and Mooney, H. A., 2002. Principles of terrestrial ecosystem ecology. Springer-Verlag, New York.

Chapin III, F. S., Mcguire, A. D., Randerson, J., *et al.*, 2000. Arctic and boreal ecosystems of western North America as components of the climate system. Global Change Biology, 6(S1):211-223.

Chapin III, F. S., Woodwell, G. M., Randerson, J. T., *et al.*, 2006. Reconciling carbon-cycle concepts, terminology, and methods. Ecosystems, 9:1041-1050.

Charman, D., 2002. Peatlands and environmental change. John Wiley & Sons, Chichester.

Chimner, R. A. and Cooper, D. J., 2003. Influence of water table levels on CO_2 emissions in a Colorado subalpine fen: an in situ microcosm study. Soil Biology & Biochemistry, 35(3):345-351.

Chimner, R. A. and Welker, J. M., 2005. Ecosystem respiration responses to experimental manipulations of winter and summer precipitation in a Mixedgrass Prairie, WY, USA. Biogeochemistry, 73(1):257-270.

Christensen, T. R., Johansson, T., A ° kerman, H. J.*, et al.*, 2004. Thawing sub-arctic permafrost: Effects on vegetation and methane emissions. Geophysical Research Letters, 31(L04501), doi:10.1029/2003GL018680.

Clein, J. S., Kwiatkowski, B. L., McGuire, A. D*., et al.*, 2000. Modelling carbon responses of tundra ecosystems to historical and projected climate: a comparison of a plot- and a global-scale ecosystem model to identify process-based uncertainties. Global Change Biology, 6(S1):127-140.

Clymo, R., 1984. The limits to peat bog growth. Philosophical Transactions of the Royal Society, B 303:605-654.

Clymo, R., Turunen, J. and Tolonen, K., 1998. Carbon accumulation in peatland. Oikos, 81:368-388.

Comer, N. T., Lafleur, P. M., Roulet, N. T*., et al.*, 2000. A test of the Canadian Land Surface Scheme (CLASS) for a variety of wetland types. Atmos. Ocean, 38(1):161-179.

Cowardin, L. M., Carter, V., Golet, F. C*., et al.*, 1979. Classification of Wetlands and Deepwater Habitats of the United States, U.S. Department of the Interior,U.S. Fish and Wildlife Service, Office of Biological Services, Washington, DC.

Cox, P. M., 2001. Description of the TRIFFID Dynamic Global Vegetation Model, Hadley Center, Bracknell.

Cox, P. M., Betts, R. A., Jones, C. D*., et al.*, 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature, 408(6809):184-187.

DeFries, R. S., Houghton, R. A., Hansen, M. C*., et al.*, 2002. Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s. Proceedings of the National Academy of Sciences, 99(22):14256-14261.

Denman, K., Brasseur, G., Chidthaisong, A.*, et al.*, 2007. Coupling between changes in the climate system and biogeochemistry. In: Solomon, S., Qin, D., Manning, M.*, et al.* (Editor), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 499-587.

Farquhar, G. D. and von Caemmerer, S., 1982. Modelling of photosynthetic response to the environment,. In: Lange, O. L., Nobel, P. S., Osmond, C. B.*, et al.* (Editor), Encyclopedia of Plant Physiology, New Series. Springer-Verlag, Berlin, 549–587.

Farquhar, G. D., von Caemmerer, S. and Berry, J. A., 1980. A biochemical model of photosynthesis CO_2 assimilation in leaves of C3 plants. Planta 149:78-90.

Flato, G. M. and Boer, G. J., 2001. Warming Asymmetry in Climate Change Simulations. Geophysical Research Letters, 28:195-198.

Foley, J. A., Prentice, I. C., Ramankutty, N.*, et al.*, 1996. An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics (IBIS). Global Biogeochemical Cycles, 10(4):603-628.

Fraser, C. J. D., Roulet, N. T. and Moore, T. R., 2001. Hydrology and dissolved organic carbon biogeochemistry in an ombrotrophic bog. Hydrological Processes, 15(16):3151-3166.

Frey, K. E. and Smith, L. C., 2005. Amplified carbon release from vast West Siberian peatlands by 2100. Geophysical Research Letters, 32(L09401), doi:10.1029/2004GL022025.

Friedlingstein, P., Cox, P., Betts , R.*, et al.*, 2006. Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison. J. Climate, 19:3337-3353.

Frolking, S., Bubier, J. L., Crill, P. M.*, et al.*, 2002. Modeling seasonal to annual carbon balance of Mer Bleue Bog, Ontario, Canada. Global Biogeochemical Cycles, 16(3), doi:10.1029/2001GB001457.

Frolking, S., Goulden, M. L., Wofsy, S. C.*, et al.*, 1996. Modelling temporal variability in the carbon balance of a spruce/moss boreal forest. Global Change Biology, 2:343-366.

Frolking, S., Lavoie, M., Muller, S. D.*, et al.*, 2001. Modeling northern peatland decomposition and peat accumulation. Ecosystems, 4(5):479-498.

Frolking, S., Roulet, N. and Lawrence, D., in press. Issues related to incorporating northern peatlands into global climate models. In: Baird, A. J., Belyea, L. R., Comas, X.*, et al.* (Editor), AGU monograph: Northern peatlands and carbon cycling. AGU.

Frolking, S. and Roulet, N. T., 2007. Holocene radiative forcing impact of northern peatland carbon accumulation and methane emissions. Global Change Biology, 13(5):1079-1088.

Frolking, S., Roulet, N. T. and Fuglestvedt, J., 2006. How northern peatlands influence the Earth's radiative budget: Sustained methane emission versus sustained carbon sequestration. Journal of Geophysical Research, 111(G01008), doi:10.1029/2005JG000091.

Gedney, N. and Cox, P. M., 2003. The sensitivity of global climate model simulations to the representation of soil moisture heterogeneity. Journal of Hydrometeorology, 4(6):1265-1275.

Gedney, N., Cox, P. M. and Huntingford, C., 2004. Climate feedback from wetland methane emissions. Geophysical Research Letters, 31(L20503), doi:10.1029/2004GL020919.

Gifford, R. M., 1994. The global carbon cycle: a viewpoint on the missing sink. Australian Journal of Plant Physiology, 21:1-15, doi:10.1071/PP9940001.

Gorham, E., 1991. Northern peatlans: role in the carbon cycle and probable responses to climatic warming. Ecological Applications, 1:182-195.

Granberg, G., Nilsson, M., Mikkela, C.*, et al.*, 1997. Sources of spatial variation in methane emission from mires in northern Sweden: a mechanistic approach in statistical modeling. Global Biogeochemical Cycles, 11(2):135-150.

Granberg, G., Sundh, I., Svensson, B. H., *et al.*, 2001. Effects of temperature, and nitrogen and sulfur deposition, on methane emission from a boreal mire. Ecology(82):1982-1998.

Gunnarsson, U., Bronge, L. B., Rydin, H., *et al.*, 2008. Near-zero recent carbon accumulation in a bog with high nitrogen deposition in SW Sweden. Global Change Biology, 14(9):2152-2165.

Hagen, S., Braswell, B., Linder, E., *et al.*, 2006. Statistical uncertainty of eddy flux-based estimates of gross ecosystem carbon exchange at Howland Forest. Journal of Geophysical Research D: Atmospheres, 111(D08S03), doi:10.1029/2005JD006154.

Halsey, L., Vitt, D. and Zoltai, S., 1997. Climatic and physiographic controls on wetland type and distribution in Manitoba, Canada. Wetlands, 17(2):243-262.

Halsey, L. A., Vitt, D. H. and Bauer, I. E., 1998. Peatland initiation during the holocene in continental western Canada. Climatic Change, 40(2):315-342.

Harley, P. C., Tenhunen, J. D. and Lange, O. L., 1986. Use of an analytical model to study limitations on net photosynthesis in Arbutus unedo under field conditions. Oecologia, 70:393-401.

Hayward, P. M. and Clymo, R., 1982. Profiles of water content and pore size in *Sphagnum* and peat, and their relation to peat bog ecology. Proc. Roy. Soc. Lond. B. Bio., 215(1200):299-325.

Heijmans, M. M. P. D., Berendse, F., Arp, W. J., *et al.*, 2001. Effects of Elevated Carbon Dioxide and Increased Nitrogen Deposition on Bog Vegetation in the Netherlands. Journal of Ecology, 89(2):268-279.

Hilbert, D. W., Roulet, N. and Moore, T., 2000. Modelling and analysis of peatlands as dynamical systems. Journal of Ecology, 88(2):230-242.

Holden, J., 2005. Peatland hydrology and carbon release: why small-scale process matters. Philosophical Transactions of the Royal Society, A363:2891-2913.

Hoosbeek, M. R., Breemen, N. V., Berendse, F*., et al.*, 2001. Limited effect of increased atmospheric CO_2 concentration on ombrotrophic bog vegetation. New Phytologist, 150(2):459-463.

Houghton, R. A., 1995. Land-use change and the carbon cycle. Global Change Biology, 1(4):275-287.

Houghton, R. A., 1999. The annual net flux of carbon to the atmosphere from changes in land use 1850-1990. Tellus B, 51(2):298-313.

Houghton, R. A., Davidson, E. A. and Woodwell, G. M., 1998. Missing sinks, feedbacks, and understanding the role of terrestrial ecosystems in the global carbon balance. Global Biogeochemical Cycles, 12(1):25-34.

Humphreys, E. R., Lafleur, P. M., Flanagan, L. B*., et al.*, 2006. Summer carbon dioxide and water vapor fluxes across a range of northern peatlands. Journal of Geophysical Research, 111(G04011), doi:10.1029/2005JG000111.

Huntingford, C., Lowe, J. A., Booth, B. B. B*., et al.*, 2009. Contributions of carbon cycle uncertainty to future climate projection spread. Tellus B, 61(2):355-360.

Huttunen, J. T., Nykanen, H., Turunen, J*., et al.*, 2003. Methane emissions from natural peatlands in the northern boreal zone in Finland, Fennoscandia. Atmospheric Environment, 37:147-151.

Ingram, H. A. P., 1978. Soil layers in mires: function and terminology. J. Soil Sci., 29:224-227.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., Qin, D., Manning, M*., et al.* (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 p.

Ise, T., Dunn, A. L., Wofsy, S. C*., et al.*, 2008. High sensitivity of peat decomposition to climate change through water-table feedback. Nature Geosci, 1(11):763-766.

Jarvis, P. G., 1976. The interpretation of leaf water potential and stomatal conductance found in canopies in the field. Philosophical Transactions of the Royal Society, B273:593-610.

Jassal, R. S., Black, T. A., Novak, M. D., *et al.*, 2008. Effect of soil water stress on soil respiration and its temperature sensitivity in an 18-year-old temperate Douglas-fir stand. Global Change Biology, doi:10.1111/j.1365-2486.2008.01573.x.

Joosten, H. and Clarke, D., 2002. Wise use of mires and peatlands-backgrounds and principles including a framework for decision-making. International Mire Conservation Group and International Peat Society, Finland.

Jury, W. A. and Horton, R., 2004. Soil physics. John Wiley & Son Inc., New Jersey, 366 p.

Kaplan, J. O., 2002. Wetlands at the Last Glacial Maximum: Distribution and methane emissions. Geophysical Research Letters, 29(6), doi:10.1029/2001GL013366.

Kim, S.-J., Flato, G. M., Boer , G. J., *et al.*, 2002. A coupled climate model simulation of the Last Glacial Maximum.Part 1: transient multi-decadal response. Climate Dynamics, 19:515-537.

Knorr, W., 2000. Annual and interannual CO_2 exchanges of the terrestrial biosphere: process based simulations and uncertainties. Global Ecol. Biogeography, 9:225-252.

Lafleur, P. M., Moore, T. R., Roulet, N. T., *et al.*, 2003. Interannual variability in the peatland-atmosphere carbon dioxide exchange at an ombrotrophic bog. Global Biogeochemical Cycles, 17(2), doi:10.1029/2002GB001983.

Lafleur, P. M., Moore, T. R., Roulet, N. T., *et al.*, 2005. Ecosystem respiration in a cool temperate bog depends on peat temperature but not water table. Ecosystems 8(6):619-629.

Lafleur, P. M., Roulet, N. T. and Admiral, S. W., 2001. Annual cycle of CO_2 exchange at a bog peatland. Journal of Geophysical Research D: Atmospheres, 106(3):3071-3081.

Lafleur, P. M., Skarupa, M. R. and Verseghy, D. L., 2000. Validation of the Canadian Land Surface Scheme (CLASS) for a Subarctic Open Woodland. Atmos. Ocean, 38(1):205-225.

Lehner, B. and Doll, P., 2004. Development and validation of a global database of lakes, reservoirs and wetlands. Journal of Hydrology, 296(1-4):1-22.

Letts, M. G., Roulet, N. T., Comer, N. T.*, et al.*, 2000. Parameterization of peatland hydraulic properties for the Canadian Land Surface Scheme. Atmos. Ocean, 38(1):141-160.

Levin, S. A., 1998. Ecosystems and the biosphere as complex adaptive systems. Ecosystems, 1(5):431-436.

Lewis, S. L., 2006. Tropical forests and the changing earth system. Philosophical Transactions of the Royal Society, B361:195-210.

Limpens, J., Berendse, F., Blodau, C.*, et al.*, 2008. Peatlands and the carbon cycle: from local processes to global implications – a synthesis. Biogeosciences 5:1475-1491.

Luca, B., 2008. A climatic threshold triggers the die-off of peat mosses during an extreme heat wave. Global Change Biology, 14(11):2688-2695.

Luo, Y., Gerten, D., Le Maire, G.*, et al.*, 2008. Modeled interactive effects of precipitation, temperature, and CO_2 on ecosystem carbon and water dynamics in different climatic zones. Global Change Biology, 14(9):1986-1999.

Malmer, N., Johansson, T., Olsrud, M.*, et al.*, 2005. Vegetation, climatic changes and net carbon sequestration in a North-Scandinavian subarctic mire over 30 years. Global Change Biology, 11(11):1895-1909.

Malmer, N. and Wallen, B., 1999. The dynamics of peat accumulation on bogs: Mass balance of hummocks and hollows and its variation throughout a millennium. Ecography, 22(6):736-750.

Matthews, E. and Fung, I., 1987. Methane emission from natural wetlands: global distribution area and environmental characteristics of sources. Global Biogeochemical Cycles, 1:61-86.

Matthews, H. D., 2005. Decrease of emissions required to stabilize atmospheric CO_2 due to positive carbon cycle-climate feedbacks. Geophysical Research Letters, 32(L21707), doi:10.1029/2005GL023435.

Matthews, H. D., Eby, M., Weaver, A. J*., et al.*, 2005. Primary productivity control of simulated carbon cycle - climate feedbacks. Geophysical Research Letters, 32(L14708), doi:10.1029/2005GL022941.

McGuire, A. D., Chapin III, F. S., Walsh, J. E*., et al.*, 2006. Integrated regional changes in arctic climate feedbacks: implications for the global climate system. Annual Review of Environment and Resources, 31:61-91.

McGuire, A. D., Walsh, J., Kimball, J*., et al.*, 2008. The Western Arctic Linkage Experiment (WALE): overview and synthesis. Earth Interactions, 12, doi: 10.1175/2008EI239.1.

McMullen, J., Barber, K. and Johnson, B., 2004. A paleoecological perspective of vegetation succession on raised bog microforms. Ecological Monographs, 74:45-77.

Medlyn, B. E., Dreyer, E., Ellsworth, D*., et al.*, 2002. Temperature response of parameters of a biochemically based model of photosynthesis, II, A review of experimental data. Plant Cell Environ., 25:1167-1179.

Meehl, G. A., Stocker, T. F., Collins, W. D*., et al.*, 2007. Global climate projections. In: Solomon, S., Qin, D., Manning, M*., et al.* (Editor), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge,United Kingdom and New York, NY, USA, 499-587.

Mikaloff-Fletcher, S. E., Tans, P. P., Bruhwiler, L. M*., et al.*, 2004. CH_4 sources estimated from atmospheric observations of CH_4 and its $^{13}C/^{12}C$ isotopic ratios:2. Inverse modeling of CH_4 fluxes from geographical regions. Global Biogeochemical Cycles, 18(GB4005), doi:10.1029/2004GB002224.

Mitsch, W. J. and Gosselink, J. G., 2000. Wetlands (Third edition). John Wiley & Sons, New York.

Moore, T. and Basiliko, N., 2006. Decomposition in boreal peatlands In: Wieder, R. and Vitt, D. H. (Editor), Boreal peatland ecosystems. Springer, New York, 126-143.

Moore, T. and Dalva, M., 1993. The influence of temperature and water table position on carbon dioxide and methane emissions from laboratory columns of peatland soils. Journal of Soil Science, 44:651-664.

Moore, T. R., Bubier, J., Frolking, S*., et al.*, 2002. Plant biomass and production and CO_2 exchange in an ombrotrophic bog. J. Ecol., 90:25-36.

Moore, T. R., Lafleur, P. M., Poon , D. M. I*., et al.*, 2006. Spring photosynthesis in a cool temperate bog. Global Change Biology, 12(12):2323-2335.

Moore, T. R. and Roulet, N. T., 1993. Methane flux: water table relations in northern wetlands. Geophysical Research Letters, 20(7):587-590.

Moore, T. R., Roulet, N. T. and Waddington, J. M., 1998. Uncertainty in predicting the effect of climatic change on the carbon cycling of Canadian peatlands. Climatic Change, 40(2):229-245.

Moren, A. S. and Perttu, K. L., 1994. Regional temperature and radiation indices and their adjustment to horizontal and inclined forest land,. Stud. For. Suecia, 194:19.

Mott, R. J. and Camfield, M., 1969. Palynological Studies in the Ottawa Area. Geological Survey of Canada, Ottawa, 1-16.

National Wetlands Working Group, 1988. Wetlands of Canada. Ecological Land Classification Series No. 24, Sustainable Development Branch, Canadian Wildlife Service, Conservation and Protection, Environment Canada, Ottawa.

Nilsson, M. and Bohlin, E., 2001. Betydelsen av vitmossa(*Sphagnum*) for boreala myrars kolbalans. Sveriges Lantbruksuniversitet, Umea.

Nilsson, M., Mikkela, C., Sundh, I*., et al.*, 2001. Methane emissions from Swedish mires: national and regional budgets and dependencedependence on mire vegetation. Journal of Geophysical Research, 106:20847–20860.

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-fluxes. Global Change Biology, 14(10):2317-2332, doi: 10.1111/j.1365-2486.2008.01654.x.

Nungesser, M., 2003. Modelling microtopography in boreal peatlands: Hummocks and hollows. Ecological Modelling, 165(2-3):175-207.

Ouyang, B., Roulet, N. T., Lafleur, P. M*., et al.*, in press. Modelling the water table in bogs using the Canadian Land Surface Scheme (CLASS). Hydrological Processes.

Page, S. E., Siegert, F., Rieley, J. O*., et al.*, 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature, 420(6911):61-65, doi:10.1038/nature01131.

Parmentier, F. J. W., van der Molen, M. K., de Jeu, R. A. M*., et al.*, 2009. CO_2 fluxes and evaporation on a peatland in the Netherlands appear not affected by water table fluctuations. Agricultural and Forest Meteorology, 149(6-7):1201-1208.

Price, A. G., Dunham, K., Carleton, T*., et al.*, 1997. Variability of water fluxes through the black spruce (Picea mariana) canopy and feather moss (Pleurozium schreberi) carpet in the boreal forest of Northern Manitoba. Journal of Hydrology, 196:310-323.

Randerson, J. T., Liu, H., Flanner, M. G*., et al.*, 2006. The Impact of Boreal Forest Fire on Climate Warming. Science, 314(5802):1130-1132.

Reimer, A., 2001. The role of bog plants in the exchange of carbon and water between the atmosphere and the Mer Bleue peatland. MSc thesis, McGill University, Montreal. 83

Rietkerk, M., Dekker, S. C., Wassen, M. J*., et al.*, 2004. A putative mechanism for bog patterning. American Naturalist, 163(5):699-708.

Riutta, T., Laine, J., Aurela, M*., et al.*, 2007. Spatial variation in plant community functions regulates carbon gas dynamics in a boreal fen ecosystems. Tellus B, 59B:838-852, doi: 10.1111/j.1600-0889.2007.00302.x.

Robroek, B. J. M., Schouten, M. G. C., Limpens, J*., et al.*, 2009. Interactive effects of water table and precipitation on net CO_2 assimilation of three co-occurring *Sphagnum* mosses differing in distribution above the water table. Global Change Biology, 15(3):680-691.

Roulet, N., 1990. Hydrology of a headwater basin wetland: groundwater discharge and wetland maintenance. Hydrological Processes, 4(4):387-400.

Roulet, N., 2000. Peatlands, carbon storage, greenhouse gases, and the kyoto protocol: Prospects and significance for Canada. Wetlands, 20(4):605-615.

Roulet, N., Ash, R. and Moore, T., 1992a. Low boreal wetlands as a source of atmospheric methane. Journal of Geophysical Research, 97:3739-3749.

Roulet, N., Moore, T., Bubier, J*., et al.*, 1992b. Northern Fens - Methane Flux and Climatic-Change. Tellus B, 44(2):100-105.

Roulet, N., Hardill, S. and Comer, N., 1991. Continuous measurement of the depth of water table (inundation) in wetlands with fluctuating surfaces. Hydrological Processes, 5(4):399-403.

Roulet, N., Lafleur, P. M., Richard, P. J. H*., et al.*, 2007. Contemporary carbon balance and late holocene carbon accumulation in a northern peatland. Global Change Biology, 13:397-411.

Roulet, N. and Moore, T., 2006. Browning the waters. Nature, 444(16):283-284.

Roulet, N., Munro, D. S. and Mortsch, L., 1997. Wetlands. In: Bailey, W. G. and al, e. (Editor), The surface climate of Canada. McGill-Queen's Univ. Press, Montreal, 149-171.

Roulet, N. and Woo, M. K., 1986. Hydrology of a wetland in the continuous permafrost region. Journal of Hydrology, 89(1-2):73-91.

Roy, V., Bernier, P., Plamondon, A*., et al.*, 1999. Effect of drainage and microtopography in forested wetlands on the microenvironment and growth of planted black spruce seedlings. Canadian Journal of Forest Research, 29:563-574.

Rydin, H. and Jeglum, J., 2006. The biology of peatlands. Oxford University Press, New York.

Sagerfors, J., 2007. Land-Atmosphere Exchange of CO_2 , Water and Energy at a Boreal Minerotrophic Mire. Ph.D thesis, Swidish University of Agricultural Science, Umea. 70pp

Sagerfors, J., Lindroth, A., Grelle, A.*, et al.*, 2008. Annual CO_2 exchange between a nutrient-poor, minerotrophic, boreal mire and the atmosphere. Journal of Geophysical Research, 113(G01001), doi:10.1029/2006JG000306.

Sarmiento, J. L. and Gruber, N., 2002. Sinks for anthropogenic carbon. Physics today, 58(8):30-36.

Schimel, D. S., House, J. I., Hibbard, K. A.*, et al.*, 2001. Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. Nature, 414(6860):169-172, doi:10.1038/35102500.

Schindler, D. W., 1999. The mysterious missing sink. Nature, 398:105-106.

Schlesinger, W. H., 1997. Biogeochemistry: An Analysis of Global Change. Academic, San Diego,California.

Schuur, E. A. G., Bockheim, J., Canadell, J. G.*, et al.*, 2008. Vulnerability of Permafrost Carbon to Climate Change:Implications for Global Carbon Cycle. BioScience, 58(8):701-714, doi:10.1641/B580807.

Schuur, E. A. G., Vogel, J. G., Crummer, K. G.*, et al.*, 2009. The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. Nature, 459(7246):556-559, doi:10.1038/nature08031.

Shindell, D. T., Walter, B. P. and Faluvegi, G., 2004. Impacts of climate change on methane emissions from wetlands. Geophysical Research Letters, 31(L21202), doi:10.1029/2004GL021009.

Silvola, J., 1990. Combined effects of varying water content and CO_2 concentration on photosynthesis in *Sphagnum* fuscum. Holarctic Ecol., 13:224-228.

Smith, L. C., MacDonald, G. M., Velichko, A. A.*, et al.*, 2004. Siberian peatlands a net carbon sink and global methane source since the early Holocene. Science, 303(5656):353-356.

Sokolov, A. P., D.W. Kicklighter, J.M. Melillo*, et al.*, 2008. Consequences of considering carbon-nitrogen interactions on the feedbacks between climate and the terrestrial carbon cycle. J. Climate, 21:3776-3796.

Sonnentag, O., 2008. Spatially explicit simulation of peatland hydrology and carbon dioxide exchange. Ph.D thesis, University of Toronto, Toronto. 229

St-Hilaire, F., Wu, J., Roulet, N. T., *et al.*, 2008. McGill Wetland Model: Evaluation of a peatland carbon simulator developed for global assessments. Biogeosciences Discuss, 5:1689-1725.

Strack, M. and Price, J. S., 2009. Moisture controls on carbon dioxide dynamics of peat-*Sphagnum* monoliths. Ecohydrology, 2(1):34-41.

Strack, M., Waddington, J. M. and Tuittila, E. -S., 2004. Effect of water table drawdown on northern peatland methane dynamics: Implications for climate change. Global Biogeochemical Cycles, 18(GB4003), doi:10.1029/2003GB002209.

Syed, K. H., Flanagan, L. B., Carlson, P. J., *et al.*, 2006. Environmental control of net ecosystem CO_2 exchange in a treed, moderately rich fen in northern Alberta. Agricultural and Forest Meteorology, 140(1-4):97-114.

Tenhunen, J. D., Weber, J. A., Yocum, C. S., *et al.*, 1976. Development of a photosynthesis model with an emphasis on ecological application, II, Analysis of a data set describing the Pm surface. Oecologia, 26:101-109.

Thornton, P., Lamarque, J.-F., Rosenbloom, N., *et al.*, 2007. Influence of carbon-nitrogen cycle coupling on land model response to CO_2 fertilization and climate variability. Global Biogeochemical Cycles, 21(GB4018), doi:10.1029/2006GB002868.

Tuittila, E. -S., Vasander, H. and Laine, J., 2004. Sensitivity of C sequestration in reintroduced *Sphagnum* to water-level variation in a cutaway peatland. Restoration Ecology, 12(4):483-493.

Turunen, J., Tahvanainen, T., Tolonen, K., *et al.*, 2001. Carbon accumulation in West Siberian mires, Russia. Global Biogeochemical Cycles, 15(2):285-296.

Turunen, J., Tomppo, E., Tolonen, K., *et al.*, 2002. Estimating carbon accumulation rates of undrained mires in Finland - application to boreal and subarctic regions. Holocene, 12(1):69-80.

Verseghy, D. L., 1991. CLASS - A Canadian Land Surface Scheme for GCMs. I. Soil model. Int. J. Climatology, 11:111-133.

Verseghy, D. L., McFarlane, N. A. and Lazare, M., 1993. CLASS - A Canadian Land Surface Scheme for GCMs. II. Vegetation model and coupled runs. Int. J. Climatology, 13:347-370.

Viney, N. R. and Sivapalan, M., 2004. A framework for scaling of hydrologic conceptualizations based on a disaggregation-aggregation approach. Hydrological Processes, 18(8):1395-1408.

Vitt, D. H., 2006. Functional characteristics and indicators of boreal peatlands. In: Wieder, R. K. and Vitt, D. H. (Editor), Boreal peatland ecosystems. Springer-Verlag, Berlin Heidelberg, 47-65.

Waddington, J. and Roulet, N., 1996. Atmosphere-wetland carbon exchanges: scale dependency of CO_2 and CH_4 exchange on the developmental topography of a peatland. Global Biogeochemical Cycles, 10(2):233-245.

Waddington, J. M. and Price, J. S., 2000. Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. Physical Geography, 21(5):433-451.

Walter, B. P. and Heimann, M., 2000. A process-based, climate-sensitive model to derive methane emissions from natural wetlands: Application to five wetland sites, sensitivity to model parameters, and climate. Global Biogeochemical Cycles, 14(3):745-765.

Walter, B. P., Heimann, M. and Matthews, E., 2001. Modeling modern methane emissions from natural wetlands 2. Interannual variations 1982-1993. Journal of Geophysical Research D: Atmospheres, 106(24):34207-34219.

Walter, K. M., Edwards, M. E., Grosse, G*., et al.*, 2007. Thermokarst Lakes as a Source of Atmospheric CH_4 During the Last Deglaciation. Science, 318(5850):633-636.

Walter, K. M., Zimov, S. A., Chanton, J. P*., et al.*, 2006. Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. Nature, 443(7107):71-75, doi:10.1038/nature05040.

Wania, R., Ross, I. and Prentice, I. C., in press. Integrating peatlands and permafrost into a dynamic global vegetation model:II.Evaluation and sensitivity of vegetation and carbon cycle processes. Global Biogeochemical Cycles.

Warnant, P., Francois, L., Gerard, J.-C., *et al.*, 1994. A global model of terrestrial biological productivity. Global Biogeochemical Cycles, 8 (3):255-270.

Warrach, K., Stieglitz, M., Mengelkamp, H. T., *et al.*, 2002. Advantages of a topographically controlled runoff simulation in a soil-vegetation-atmosphere transfer model. Journal of Hydrometeorology, 3(2):131-148.

Weltzin, J., Harth, C., Bridgham, S., *et al.*, 2001. Production and microtopography of bog bryophytes: response to warming and water-table manipulations. Oecologia, 128:557-565.

Weltzin, J. F., Harth, C., Bridgham, S. D., *et al.*, 2003. Potential effects of warming and drying on peatland plant community composition. Global Change Biology, 9(2):141-151.

Weltzin, J. F., Updegraff, K., Chapin, C. T., *et al.*, 2000. Response of bog and fen plant communities to warming and water-table manipulations. Ecology, 81(12):3464-3478.

Williams, T. G. and Flanagan, L. B., 1998. Measuring and modelling environmental influences on photosynthetic gas exchange in *Sphagnum* and *Pleurozium*. Plant Cell Environ., 21:555-564, doi:10.1046/j.1365-3040.1998.00292.x.

Willmott, C. J., 1982. Some comments on the evaluation of model performance. Bull. Am. Meteorol. Soc., 63(11):1309-1313.

Willmott, C. J., 1985. Statistics for the evaluation and comparion of models. Journal of Geophysical Research, 90(C5):8995-9005.

Wood, E. F., Lettenmaier, D. P. and Zartarian, V. G., 1992. A land-surface hydrology parameterization with subgrid variability for general circulation models. Journal of Geophysical Research, 97(D3):2717-2728.

Worrall, F., Reed, M., Warburton, J., *et al.*, 2003. Carbon budget for a British upland peat catchment. Science of the Total Environment, 312:133-146.

Yeh, P. J. F. and Eltahir, E. A. B., 2005. Representation of water table dynamics in a land surface scheme. Part II: Subgrid variability. Journal of Climate, 18(12):1881-1901.

Yi, S., Manies, K., Harden, J*., et al.*, 2009. Characteristics of organic soil in black spruce forests: Implications for the application of land surface and ecosystem models in cold regions. Geophysical Research Letters, 36(L05501), doi:10.1029/2008GL037014.

Yu, Z. C., 2006. Modeling ecosystem processes and peat accumulation in boreal peatlands. In: Wieder, R. K. and Vitt, D. H. (Editor), Boreal peatland ecosystems. Springer-Verlag, Berlin Heidelberg, 313-329.

Yu, Z. C., Vitt, D. H., Campbell, C*., et al.*, 2000. Pattern and processes of peat accumulation in continental rich fen:hypothesis and preliminary results. In: Rochefort, L. and Daigle, J. Y. (Editor), the 11th international peat congress. The international peat society, Quebec city, 208-215.

Yu, Z. C., Vitt, D. H., Campbell, I. D*., et al.*, 2003. Understanding Holocene peat accumulation pattern of continental fens in western Canada. Canadian Journal of Botany, 81(3):267-282.

Yurova, A., Wolf, A., Sagerfors, J*., et al.*, 2007. Variations in net ecosystem exchange of carbon dioxide in a boreal mire: Modeling mechanisms linked to water table position. Journal of Geophysical Research, 112(G02025), doi:10.1029/2006JG000342.

Zhang, Y., Li, C., Trettin, C*., et al.*, 2002. An integrated model of soil,hydrology,and vegetation for carbon dynamics in wetland ecosystems. Global Biogeochemical Cycles, 16, DOI:10.1029/2001GB001838.

Zoltai, S. and Vitt, D., 1990. Holocene climatic change and the distribution of peatlands in western interior Canada. Quaternary Research, 33(2):231-240.

Appendix - McGill Wetland Model: Evaluation of a peatland carbon simulator developed for global assessments

Francois St-Hilaire [1,2], Jianghua Wu [1,2] , Nigel T. Roulet [1,2,3] *, Steve Frolking [4], Peter M. Lafleur [5], Elyn R. Humphreys [6], and Vivek Arora[7]

1. Department of Geography, McGill University, 805 Sherbrooke Street West, Montreal, QC H3A 2K6, Canada

2. The Global Environment and Climate Change Centre, McGill University, Montreal, QC Canada

3. McGill School of Environment, McGill University, Montreal QC Canada

4. Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824 USA.

5. Department of Geography, Trent University, 1600 Westbank Drive, Peterborough, ON K9J 7B8 Canada

6. Department of Geography & Environmental Studies, Carleton University, B349 Loeb Building, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada

7. Canadian Centre for Climate Modelling and Analysis (CCCma), Environment Canada, PO Box 1700, STN CSC, Victoria BC V8W 2Y2

* corresponding author: Nigel Roulet, Department of Geography, McGill University, 805 Sherbrooke St W. Montreal, QC H3A 2K6 Canada (nigel.roulet@mcgill.ca; 514-398-4945)

ABSTRACT

We developed the McGill Wetland Model (MWM) based on the general structure of the Peatland Carbon Simulator (PCARS(and the Canadian Terrestrial Ecosystem Model. Three major changes were made to PCARS: 1. the light use efficiency model of photosynthesis was replaced with a biogeochemical description of photosynthesis; 2. the description of autotrophic respiration was changed to be consistent with the formulation of photosynthesis; and 3. the cohort, multilayer soil respiration model was changed to a simple one box peat decomposition model divided into an oxic and anoxic zones by an effective water table, and a one-year residence time litter pool. MWM was then evaluated by comparing its output to the estimates of net ecosystem production (NEP), gross primary production (GPP) and ecosystem respiration (ER) from 8 years of continuous measurements at the Mer Bleue peatland, a raised ombrotrophic bog located in southern Ontario, Canada (index of agreement [dimensionless]: NEP=0.80, GPP=0.97, ER=0.97; systematic RMSE [g C m^{-2} d^{-1}]: NEP=0.12, GPP=0.07, ER=0.14; unsystematic RMSE [g C m^{-2} d^{-1}]: NEP=0.15, GPP=0.27, ER=0.23). Simulated moss NPP approximates what would be expected for a bog peatland, but shrub NPP appears to be underestimated. Sensitivity analysis revealed that the model output did not change greatly due to variations in water table because of offsetting responses in production and respiration, but that even modest temperature increases could lead to converting the bog from a sink to a source of CO_2. General weaknesses and further developments of MWM are discussed.

INTRODUCTION

Over the last decade, the carbon (C) cycle in terrestrial and ocean ecosystems has been incorporated into a number of global climate simulations showing general agreement of a positive carbon cycle-climate feedback between the terrestrial biosphere and oceans and the atmosphere, but with large variations in the magnitude of the resulting CO_2 increase in the atmosphere (Friedlingstein et al. 2006). It has been generally acknowledged that while most of the terrestrial models capture the essence of the C cycle they lack many processes and components that may be critical to a more realistic assessment (Thornton et al. 2007; Denman et al. 2007). A recent example of a factor not included in the early coupled terrestrial C climate models that has a very high leverage on size of the positive feedback is the inclusion of a nitrogen cycle (Thornton et al. 2007). Additionally, land-use and land cover change, permafrost dynamics, and some critical but presently excluded ecosystems such as wetlands are believed to be important. Northern peatlands, the dominant form of wetland above ~ 45° N though they also occur in tropical regions, have not been included. This is in part because they represent < 4% of the global land surface (Gorham 1995).

While the present day net primary production (NPP) of northern peatlands may represent < 1% of total terrestrial NPP, the amount of organic C stored in peatlands is very large relative to any other terrestrial biome or ecosystem – i.e. between ~ 250 and 450 Pg C, or 10 to 20% (Gorham 1991, Turunen et al. 2002) of a ~ 2,300 Pg C total (Denman et al., 2007). The maintenance of this store of C is in large part a function of the moisture conditions of peatlands. If moisture were to change due to climate change, it is expected that the C uptake or release and methane (CH_4) emissions increase or decrease resulting from wetter or dryer conditions respectively (Moore et al. 1998). A change in stored C by 5% could represent 12 to 25 Pg C. Unfortunately, unlike forested and grassland ecosystem biogeochemistry models, there has been little effort in developing models of peatland biogeochemistry that are suitable for use in climate simulations (e.g. Frolking et al. 2002). In this paper we develop a model, based on the general Peatland Carbon Model (PCARS: Frolking et al., 2002), but that has the same general structural and functional components as the Canadian Terrestrial Ecosystem Model (CTEM: Arora 2003, Arora and Boer 2005a & b, 2006), the terrestrial C model developed for inclusion in the Canadian Centre for Climate and Model Analysis (CCCma) coupled general circulation model. Eventually a MWM-like model would be incorporated into CTEM if the general climate models are sufficient to support the hydrological needs of wetland simulation in climate change scenarios.

Peat is the remains of partially decomposed plants and it accumulates because the NPP of a peatland exceeds decomposition, on average. Decomposition in peatlands is slow because of the persistence of anoxic conditions throughout most of the peat profile due to the saturated conditions inhibiting the diffusion of oxygen; therefore the hydrology of the ecosystem is critical to the cycling of C. In addition, many peatland plants, particularly the *Sphagnum* mosses that grow on the ombrotrophic (i.e. rain-fed, and/or nutrient poor peatlands) are much more resistant to decomposition than the foliar tissues of vascular plants (Moore and Basiliko, 2006). As litter is added to the peat profile the peatland surface continues to grow in height. As the litter decomposes it loses its original structure leading to a dramatic change in the pore size distribution at the long-term position of the water table. This effectively creates two layers of peat: a deep and thick anoxic zone called the catotelm and a shallow, thin, surface oxic zone called the acrotelm (Ingram 1978). To simulate decomposition in peatlands it is essential that there be an adequate description of the hydrology of these layers of a peatland, particularly the day-to-day and seasonal variability in the position of the water table. In other work we have modified the Canadian Land Surface Scheme (CLASS) for the inclusion of organic soils and the estimation of the water table for both fen and bog type peatlands – the two dominant forms of northern peatlands (Letts et al. 2000; Comer et al. 2000; Ouyang et al, in press). Once the water table is known a model needs to be able to capture the differences in the rates of decomposition caused by the differences in anaerobic conditions down through the peat profile and the progressively more recalcitrant residual material that dominates at depth.

In addition to the reduction in decomposition in peatlands, a model of peatland C dynamics needs to account for the uniqueness in the plants that inhabit peatlands. Peatland vegetation is characterized by sedges, herbs, deciduous and evergreen shrubs, the latter often represented by ericaceous shrubs, mosses that are usually *Sphagnum* in the more nutrient poor acidic peatlands, and conifer trees, if trees are present. Most terrestrial ecosystem models can adequately represent photosynthesis and respiration for sedges using the function for grasses, and deciduous shrubs and conifers, but they lack the attributes of plant functional types that capture the behaviour of ericaceous shrubs and mosses. Mosses present a further problem, as they have no roots or vascular system.

The Canadian Terrestrial Ecosystem Model (CTEM) is representative of the general structure and function of class of terrestrial ecosystem models used in global couple climate simulations (Aurora 2003). CTEM has three live C components: leaves, stem and roots; and two dead C components: litter and soil. Photosynthesis is based on the biogeochemical approach (Farquhar et al. 1980, Collatz et al. 1991, 1992) with coupled photosynthesis-stomatal conductance and a description of moisture stress. Autotrophic respiration is the sum of maintenance respiration for the three live components and growth respiration. Heterotrophic respiration is the sum of respiration from a litter pool and a single soil pool, with base respiration rates modified by soil or litter temperature and moisture. To adapt PCARS closer to the structure and approach of CTEM we have: 1) replaced the light use efficiency approach for photosynthesis in PCARS with the biogeochemical approach used in CTEM and then developed the parameters for the biogeochemical model for typical peatland plants: sedges, ericaceous shrubs, mosses; 2) modified the description of autotrophic respiration to be consistent with the new formulation for photosynthesis; and 3) converted the cohort, multi-layer soil respiration model used in PCARS (the Peat Decomposition Model: Frolking et al. 2001) to a two-compartment litter and soil respiration model, where the soil (peat) is partitioned into an oxic and anoxic zone using an effective water table.

In this paper we first describe the model developments and then evaluate the performance of the MWM with the plant functional types for an ombrotrophic bog – the Mer Bleue peatland of the Fluxnet Canada and Canadian Carbon Project research networks (Lafleur et al. 2001, 2003; Roulet et al. 2007). We then examine the sensitivity of the model to changes in ‘key’ environmental variables such as temperature and water table. We conclude with a brief discussion of how the model could be extended to other peatland types and how the MWM might be adapted for use in regional or global analyses.

McGILL WETLAND MODEL (MWM)

The MWM comprises four C pools: two living matter pools– vascular plants comprising leaves, sapwood and roots, and moss, as well as two dead matter pools –litter and peat. C enters the system through photosynthesis of vascular plants and mosses and leaves via either autotrophic respiration or heterotrophic respiration. The C allocation in roots and leaves and the simple growing degree-days approach for the seasonal phenology of vascular plants follow PCARS: a fixed maximum and minimum threshold, $B_{max\,foliar}$ *and* $B_{min\,foliar}$, respectively, bound the foliar biomass of a given vascular plant and $B_{max\,foliar}$ determines in turn the root biomass. Sapwood volume (B_{stem}) is a fixed parameter throughout the simulations. Moss capitulum biomass (B_{moss}) is also fixed and photosynthesises whenever environmental conditions permit. Once the vascular plant tissue and moss die they become litter and are decomposed for one year in a litter pool and then transferred to the peat C pool. At present the MWM has four plant functional types (PFTs): mosses, sedges, shrubs, and conifer trees. The details of the processes that are substantially changed from PCARS to MWM are described below.

Photosynthesis

MWM computes the photosynthesis for each PFT at an hourly time step based on the Farquhar biochemical approach (Farquhar et al. 1980, Collatz et al. 1991, 1992). The computation for the non-vascular PFT is slightly different since mosses do not possess stomata. For mosses, a semi-empirical model including the effects of water content on photosynthetic capacity (Tenhunen et al. 1976) and on total conductance to CO_2 (Williams and Flanagan 1998) replaces the stomatal conductance of vascular PFTs.

For all PFTs, net photosynthesis (A_n) is expressed as:

$$A_n = V_c(1 - \frac{\Gamma_*}{C_i}) - R_d$$
$$V_c = \min(W_c, W_j) \tag{1}$$

where V_c is the rate of carboxylation of Rubisco, C_i is the intercellular CO_2 partial pressure, Γ_* is the CO_2 compensation point in the absence of mitochondrial respiration which is related to τ, the Rubisco enzyme specificity factor and oxygen concentration, $[O_2]$, through $\Gamma_* = 0.5[O_2]/\ \tau$. R_d is the dark respiration and V_c is determined by the minimum of the rate of carboxylation when limited by Rubisco activity (W_c) or RuBP regeneration via electron transport (W_j). We use the standard formula for W_c (not shown), where the key parameter in this description is V_{max25} the maximum velocity of Rubisco carboxylation at 25^0C. The rate of electron transport (W_j) (not shown) is described in Farquhar and von Caemmerer (1982). The key variable here is the potential electron transport rate J (Smith 1937), which is a function of intercepted photon flux density (I) and J_{max} the maximum light-saturated rate of electron transport whose temperature dependency is outlined by Farquhar et al. (1980) and Lloyd et al. (1995). J_{max} at 25^0C (J_{max25}) is determined from a J_{max}:V_{cmax} ratio (Medlyn et al. 2002).

Conductance of Vascular Plant Types

The canopy conductance (g_c) and boundary layer conductance (g_b) are required to obtain the C_i of vascular PFTs:

$$C_i = C_s - A_n(\frac{1.4}{g_b} - \frac{1.6}{g_c}) \tag{2}$$

$$C_s = C_a - \frac{1.4 A_n p}{g_b} \tag{3}$$

where C_s is the canopy surface CO_2 partial pressure, C_a the atmospheric CO_2 partial pressure, p is the atmospheric pressure, and the constants 1.4 and 1.6 consider the reduced diffusivity of CO_2 compared to water through the leaf surface and the canopy, respectively. C_i is evaluated through iteration. A land surface scheme would provide the value of g_b in a coupled regional or global simulation; in the stand-alone version g_b is calculated with the Ball-Berry approach (Ball et al. 1987). The Jarvis approach (Jarvis 1976) parameterized for peatlands is used to evaluate the canopy resistance (r_c), which is inversely proportional to g_c.

Soil matric potential (Ψ) used in the calculations of canopy conductance was evaluated individually for the catotelm and the acrotelm using the formulations of Campbell (1974) and Clapp and Hornberger (1978) and the parameters for peat suggested by Letts et al. (2000). A normalized water-content function, $G(\theta)$, parameterized for peatland by Letts et al. (2000) modifies gc to account for the water stress factor:

$$G(\theta) = 1 - (1-\beta)^2$$
$$\beta(\theta) = \max(0, \min(1 - \frac{\theta_l - \theta_{\lim}}{\theta_p - \theta_{\lim}})) \qquad (4)$$

where θ_{lim} is the residual soil-water content, θ_l is the volumetric soil-water content and θ_p is the soil porosity. The function is calculated independently for fibric and hemic peat and is weighted according to the root-biomass content in each of those layers. Shrub and sedge root biomass profiles from Moore et al. (2002) are used to estimate the weighting of β in our simulations. Volumetric soil-water content is evaluated at two depths (d) corresponding to the centre of fibric and hemic layers:

$$\theta_l = \theta_p (\frac{W-d}{\psi_{sat}})^{\frac{-1}{b}} \qquad (5)$$

where W is the water table depth, Ψ_{sat} is the soil matric potential at saturation and b is the soil texture parameter of the peat layer as suggested by Letts et al. (2000).

Total Conductance of Mosses

For mosses, total conductance to CO_2 (g_{tc}) is used to find C_i instead of stomatal conductance employed for vascular plants:

$$C_i = C_a - \frac{A_n}{g_{tc}} \qquad (6)$$

Total conductance is determined from a least square regression described by Williams and Flanagan (1998) as:

$$g_{tc} = -0.195 + 0.134\Theta_f - 0.0256\Theta_f^{\ 2} + 0.00228\Theta_f^{\ 3} - 0.0000984\Theta_f^{\ 4} \\ +0.00000168\Theta_f^{\ 5} \tag{7}$$

where Θ_f is the moss water content in units of g fresh moss/g dry moss (=Θ_m +1). This relationship is only valid up to the maximum holding capacity of mosses (Θ_{maxcap}). Soil-water content and the capitulum interception of atmospheric water determine the water content of mosses. A function derived from the results of an experiment done by Hayward and Clymo (1982) with *Sphagnum capillifolium* determines the moss water content from capillary rise (Θcr) in g water/g dry moss:

$$\Theta_{cr} = \max(\Theta_{\min cap}; \min(\Theta \max cap, 22\exp(-6.5W))) \tag{8}$$

where Θ_{mincap} is the minimum interception capacity for mosses. The water content in the capitulum of mosses (Θ_{ca}) is added to the total moss water content (Θ_m):

$$\Theta_m = \Theta_{ca} + \Theta_{cr} \tag{9}$$

In turn, the intercepted water pool is affected by a loss rate, k_d, due to evapotranspiration (Frolking et al. 1996):

$$\Theta_{ca}(t+1) = \min(\Theta_{\max cap}; \Theta_{ca}(t) + \frac{\rho_{water} hppt}{B_{mass}})$$

during a rain event; (10)

$$\Theta_{ca}(t+1) = \Theta_{ca}(t)\exp(-k_d t_d) \text{ otherwise,} \tag{11}$$

where t refers here to the hourly time steps, ρ_{water} is an approximation of the rain water density, *hppt* is precipitation in mm h^{-1}, t_d is the sum of the number of one-hour time steps with no precipitation. This sum is reset to zero as soon as a precipitation event occurs. If MWM were coupled to a surface climate model, equations (10) and (11) would not be necessary since they would be derived directly from the latent heat flux.

Autotrophic Respiration

The temperature dependency of the autotrophic respiration (AR) of mosses follows a Q_{10} type relationship and is further modified by the function f_{Θ} to account for the moss water content effect on respiration (Figure 2e & 2f, Frolking et al. 1996). A Q_{10} of 2.0 (Frolking et al. 2002; Arora 2003) along with the base rate respiration at 25°C, R_{d25}, are used to calculate total dark respiration at temperature T (in °C):

$$R = R_{25} f_{\Theta} Q_{10}^{(T-25)/10} \qquad (12)$$

The autotrophic respiration of other PFTs also follows a Q_{10} relationship for temperature sensitivity and is a combination of maintenance respiration of the leaves, stems, roots, and growth respiration similarly to CTEM (Arora 2003). It is closely linked to the allocation of C in the plant.

Decomposition

Heterotrophic respiration (HR) in the C stored in peat is partitioned between oxic and anoxic respiration according to the position of an effective water table. It is assumed that the mass of peat above the effective water table decomposes under oxic rates through aerobic pathways, while peat below the water table decomposes at anoxic rates through anaerobic pathways. The effective water table depth, W_{eff}, represents the position of the water table that is derived from the actual water table depth by adding the water distributed in the oxic layer expressed as depth and subtracting the air volume trapped in the anoxic layer. An hourly moisture profile is used to estimate the amount of water in the oxic compartment. Each compartment is characterized by either oxic or anoxic conditions with corresponding rates of respirations equal to:

$$R_{oxic} = k_{eff,o} f_t C_o \qquad (13)$$

$$R_{anoxic} = k_{eff,a} f_t C_{an} \qquad (14)$$

where $k_{eff,o}$ and $k_{eff,a}$ are termed the effective hourly mass loss rates in oxic and anoxic conditions, respectively, C_o and C_{an} are the carbon contents in the oxic and anoxic compartment, respectively. The temperature dependency of decomposition, f_t, is similar to that used in PCARS (Frolking et al. 2002) with the addition of a minimum temperature for decomposition (Clein and Schimel 1995). We use the peat bulk density profile based on Figure 1c in Frolking et al. (2001) to find the carbon content, which is also fractioned in the oxic and anoxic compartments accordingly with the effective water table depth:

$$C_o = frac \times (4056.6 W_{eff}{}^2 + 72067.0 W_{eff}) \tag{15}$$

$$C_{an} = frac \times (4056.6 PD^2 + 72067.0 PD) - C_o \tag{16}$$

where *PD* is the total peat depth and *frac* is the biomass to carbon ratio. Peat depth requires initialization (PD_0) and is site specific. Fresh litter is decomposed in a separate compartment for a year using equation 13, with k_{eff} replaced with an initial decomposition rate (k_0) for moss and for all other litter and *Co* is replaced with the mass of moss and all vascular plant litter, respectively. Total C content, or equivalent peat depth, is obtained by adding equations (15) and (16), by subtracting from it the loss in C due to decomposition and adding to it the remaining litter from the plants after its initial year of decomposition, and finally by solving the quadratic for PD. Fresh litter C content is therefore not included to the peat C pool in its first year.

The Peat Decomposition Model (PDM) developed by Frolking et al. (2001) is used to obtain a 'representative' vertical profile of mass loss rates for bogs and fens. The profiles are built using the long-term fixed water table depths of Frolking et al. (2001) for a representative bog and fen, but the effect of anaerobic conditions on decomposition is kept as in PDM: a modifier equal to 0.1 for fens or 0.025 for bogs is used for anoxic conditions. During the initialization of the peat profile the peat temperature profile is also assumed constant. For MWM $k_{eff,o}$ and $k_{eff,a}$ are then obtained by integrating the area under the exponential mass loss curves of the profile in the oxic and anoxic layer, respectively (e.g see Figure Frolking et al. 2001).

SITE AND DATA SETS

The fluxes of CO_2 in the MWM, such as photosynthesis and respiration, are functions of environmental drivers. These drivers can either be input to the model from measurements from a specific site or can be obtained from a land surface model or general climate model, if MWM is being run in a coupled mode. The model requires hourly weather data: air and soil temperatures, water table depth, photosynthetic photon flux density, precipitation (rain and snow), wind speed, atmospheric pressure, atmospheric CO_2 concentration, relative humidity and net radiation. A complementary data set containing model parameters based on studies reported in the literature serves for all sites within a range of general northern peatlands types (Table 1). For the purposes of the present study we run the MWM using 8 years of environmental measurements (1/1/1999 to 12/31/2006) from the Mer Bleue peatland, a 28 km^2 raised ombrotrophic bog near Ottawa, Canada (45°25'N, 75°40'W). We use the calendar year for our simulations. The climate of the region where Mer Bleue is located is cool-temperate with a mean annual temperature of 6.0°C and a mean annual precipitation of 944mm for the period 1970-2000 (www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html). Hourly weather data is taken from the MB flux tower data set (http://fluxnet.ccrp.ec.gc.ca/e_about.htm). The bog is covered by mosses (*Sphagnum capillifolium, Sphagnum magellanicum*), evergreen shrubs (*Chamaedaphne calyculata, Kalmia angustifolia,* and *Ledum groenlandicum*), and some deciduous shrubs (*Vaccinium myrtilloides*), scattered sedges (e.g. *Eriophorum vaginatum*), patches of black spruce (*Picea mariana*) and larch (*Larix laricina*) in the central part (Roulet et al. 2007). The peat depth is approximately 5 m. Total aboveground biomass for vascular species measured in 1999 and 2004 averaged 356 ± 100 g m^{-2} (Moore et al. 2002) and 433 g m^{-2} (Bubier et al. 2006). Belowground biomass in 1999 was 1820 ± 660 g m^{-2} (Moore et al. 2002). *Sphagnum* capitulum biomass in 1999 was 144 ± 30 g m^{-2} (Moore et al. 2002) and 158 g m^{-2} in 2004 (Bubier et al. 2006).

RESULTS AND DISCUSSION

We first assess how well MWM performed in capturing the annual and seasonal patterns and magnitude of C exchanges using the 8 years of continuous measurements from the Mer Bleue peatland. We examine the patterns of gross primary production (GPP), ecosystem respiration (ER), and net ecosystem exchange (NEE) and then examine the sensitivity of the MWM output to changes in the key environmental variables of moisture and temperature. Details on the measurement of NEE and how GPP and ER were derived from the NEE observations as well as the errors and uncertainties in the observations can be found in Lafleur et al. (2001, 2003) and Roulet et al. (2007). In the analysis presented below it should be noted that the uncertainty can be fairly large on GPP and ER derived from gap-filled NEE records for short time scales (hourly, daily) but the uncertainty gets much smaller for long time scales (annual) (Hagen et al. 2006).

Annual Patterns of Simulated and Measured Exchange Fluxes

We summed the daily gap-filled NEE from Mer Bleue to generate an annual net ecosystem productivity (NEP), disregarding the loss of C via methane (CH_4) emissions and net dissolved organic carbon (DOC) export, which are not yet simulated by MWM. Here we use the terminology for NEP as proposed by (Chapin et al. 2006): NEP is the difference between GPP and ER and equals –NEE. From the output of MWM we estimated net primary production (NPP) of the mosses and shrubs as the difference between their GPP and AR respectively. We can compare this simulated NPP with the annual estimates of NPP for Mer Bleue of Moore et al. (2002) and the range of NPP found in the literature for open bogs. Finally, MWM produces an output of total HR based on the sum of oxic decomposition of the first year litter and the peat located above the effective water table and anoxic decomposition from below the effective water table. At present we cannot do a complete analysis of net ecosystem C balance, NECB (Chapin et al. 2006), because we have not yet incorporated modules that partition the decomposition products into CO_2 and CH_4 fluxes, and net DOC export: currently, ER all goes to CO_2. This means MWM annual ER should exceed, on average, the eddy covariance measurements of ER by ~ 15 g C m^{-2} yr^{-1} based on the six year estimates of NECB (Roulet et al. 2007).

In general, the MWM simulates the magnitudes and interannual trend in annual NEP (Table 2). The maximum NEP underestimate was 59 g C m^{-2} yr^{-1} in 1999 and the maximum overestimate was 46 g C m^{-2} yr^{-1} in 2000. The average absolute difference between simulated and measured NEP is 39 g C m^{-2} yr^{-1}. NEP is underestimated for two of the eight years (1999, 2006) and overestimated in the other years. GPP underestimation and overestimation followed the same pattern as NEP. The mean difference between observed and simulated NEP after 8 years of simulation is only 11 g C m^{-2} yr^{-1}, or < 20%.

There are no direct measurements to evaluate how well MWM does in estimating the fractional components that make up total comprise GPP and ER, but the proportions approximate what is generally expected (Table 2). The fraction of moss and shrub GPP ranges between 0.33 and 0.39 (mean 0.36 ± 0.02) and 0.61 and 0.67 (mean 0.64 ± 0.02) of the total. AR represents over 90% of ER, with shrub respiration and moss respiration comprising on average 64 ± 1% and 27± 2% respectively. Oxic zone decomposition contributes to 96% of HR, consistent with the relative proportions of oxic and anoxic sources of CO_2 and CH_4 in the peat column from Blodau et al. (2006).

NPP, which is the difference between GPP and AR, displays a different pattern than the gross fluxes (Table 2). In the MWM simulation moss NPP represents a mean of 62% of total NPP (minimum and maximum of 49% and 89%), while shrubs NPP averages 38% (minimum and maximum of 11% and 51%). So while the contribution of moss and shrub to GPP and ER varies only slightly over the eight years (standard deviation of 0.02 and 0.01 g C m^{-2} yr^{-1}) NPP shows a much greater interannual variability (0.16 g C m^{-2} yr^{-1}). This is due to the way MWM handles growth and maintenance respiration. In the case of moss, each year the GPP goes entirely to growing new moss, which is then assumed to die at the end of the growing season; whereas shrub has a biomass that requires significant maintenance respiration and hence a smaller fraction of GPP being translated into new biomass. MWM produces lower values of shrub NPP than expected. Measurement of the annual change in biomass in peatland shrub and moss is difficult, but the expected ranges based on a synthesis of peatland NPP studies (Moore et al. 2002) are 21-169 g C m^{-2} yr^{-1} for shrub above-ground NPP and 8 -190 g C m^{-2} yr^{-1} for moss NPP, and 79-377 g C m^{-2} yr^{-1} for total NPP (assuming biomass is 50% C). For Mer Bleue, Moore et al. (2002) estimated above ground shrub and moss NPP in 1999 to be 80 and 85 g C m^{-2} yr^{-1}, respectively, while the MWM for the same year simulated 9 and 47 g C m^{-2} yr^{-1}, respectively. For the eight simulated years, the average of simulated above ground shrub and moss NPP were 95 g biomass m^{-2} yr^{-1} and 157 g biomass m^{-2} yr^{-1}, respectively. We believe this underestimation of shrub NPP occurs, in part, because of the range in which shrub foliar biomass is allowed to vary. We use the minimum and maximum values from PCARS (Frolking et al. 2002), but the range could easily be greater with the water table variability observed over the 8-year evaluation period. There is, however, a dearth of empirical observations of the fractional components of total NPP in peatlands, and as far as we know, no one to our knowledge has reported on year-to-year variations in peatland biomass, be it aboveground or simply foliar.

Seasonal and Interannual Variability of Simulated and Measured Exchange Fluxes

Simulated GPP follows a strong annual cycle with maximum daily fluxes ranging from 5.0 g C m^{-2} d^{-1} to 6.0 g C m^{-2} d^{-1} during the peak growing season to zero during the coldest months (Figure 1). Statistical analysis reveals an index of agreement of 0.97 between the simulated and the tower fluxes with a systematic root mean square error ($RMSE_s$) and an unsystematic root mean square error ($RMSE_u$) of 0.07 g C m^{-2} d^{-1} and 0.27 g C m^{-2} d^{-1}, respectively. The low systematic error is somewhat misleading as the trend of measured versus modelled values is non linear. There is a slight overestimate of simulated daily GPP for fluxes between 0 and ~ 4 to 4.5 g C m^{-2} d^{-1} and an underestimation of observed larger fluxes (> 6 g C m^{-2} d^{-1}) by 3 to 4.5 g C m^{-2} d^{-1} (Figure 2). This weakness in capturing the full range of observed variability, especially the highest hourly fluxes, is not significant on an annual time scale. The tendency for MWM to underestimate the largest GPP is partly explained by the maximum threshold defined in the model for foliar biomass. However, the maximum foliar biomass should have a seasonal, not an hourly impact. The model is built from relationships that fit curve to data, hence the tendency to be weak at capturing the full range of observed variability.

The average growing season water table depths and temperatures were ranked for the 8 years of simulation to observe if there was any correlation with the average fluxes (Table 3). The standard deviation for the average temperatures is 0.79°C and that for average water table depth is 0.06m. According to the sensitivity analysis described below only the variation in temperatures significantly affects the fluxes. In general, GPP is greater in warmer years. However, there are exceptions to this trend. 2004 has the highest simulated GPP even though it corresponds to a relatively cold year and the lowest GPP is found in 1999, which has the warmest growing season.

Examining the inter-annual variability of cumulative GPP (Figure Y-2a) reveals the consequences of limiting the range in which vascular plant foliar biomass can exist. The growing season of 2002 was extremely dry. At Mer Bleue we made casual observations that indicated there was increased leaf litter fall of the evergreen shrubs. However, MWM does not allow the foliar biomass to go below a prescribed minimum value. The following year (2003) MWM grossly over-estimated GPP. Such a result would occur if the MWM carried over too much foliar biomass from the previous year. This would increase shrub photosynthesis by having more than expected leaf area to capture light and conversely increase moss photosynthesis due to a lack of shading by the shrubs. However, shrubs account for more than 65% of overall photosynthesis. Such findings underscore the importance of drought stress on the vascular plants, which was not something we initially considered an issue. Yet, it appears that a year-to-year memory is needed to ensure a better description of the antecedent conditions for production in subsequent years.

ER shows a strong annual cycle with maximum daily fluxes ranging between -4.2 g C m^{-2} d^{-1} and -5.2 g C m^{-2} d^{-1} during the growing season and fluxes of approximately -0.25 g C m^{-2} d^{-1} during the cold season. Simulated respiration has an agreement of 0.97 with the tower flux and a $RMSE_s$ and $RMSE_u$ of 0.14 g C m^{-2} d^{-1} and 0.23 g C m^{-2} d^{-1}, respectively. Simulated respiration is biased towards carbon loss compared to tower measurements, especially during the growing season (Figure 3). There is a slight over-estimate of simulated ER for fluxes up to ~ -4 to -4.5 g C m^{-2} d^{-1}, but for a small number of observed larger fluxes (i.e. < -6 g C m^{-2} d^{-1}) MWM underestimates them by 1 to 3 g C m^{-2} d^{-1} (Figure 2). While this underestimation of the flux cannot be directly attributed to a specific modelling approach in the MWM, it may suggest the need for a stronger or different temperature dependency (e.g., a $Q_{10} > 2.0$). The highest annual fluxes are found in 1999 and 2001 and the lowest annual fluxes are in 2000 and 2004. As expected, warmer years tend to have larger ER fluxes. No correlation exists between the rankings of ER and GPP fluxes. This reflects the fact that even though both fluxes are sensitive to the temperature in a similar manner, other environmental conditions also significantly affect the annual fluxes.

Simulated daily NEP shows a strong annual cycle with maximum daily uptakes ranging between 1.5 g C m^{-2} d^{-1} and 2.5 g C m^{-2} d^{-1} during the growing season and maximum ecosystem loss of around -0.25 g C m^{-2} d^{-1} during the cold season and approximately -1.0 g C m^{-2} d^{-1} during the growing season (Figure 4). $RMSE_s$ was 0.12 g C m^{-2} d^{-1}, the $RMSE_u$ was 0.15 g C m^{-2} d^{-1} and the index of agreement 0.80 (Figure 5). The NEP of 2004 and 2005 have the highest magnitudes while the lowest NEP occurs in 1999 and 2002. Larger NEP generally occurs in the warmer years. As mentioned earlier, daily NEP is not simulated but derived from the subtraction of ER from GPP. Therefore NEP has a tendency to underestimate the highest fluxes in a similar way to GPP. NEP also accumulates the errors propagated from both GPP and ER fluxes, generating a RMSE that represents a relative error twice as large as that for GPP and ER.

Sensitivity Analysis

Sensitivity analyses were performed to assess the change in C fluxes with variations in the two main environmental parameters: water table depth and moisture supply through precipitation; and temperature, including air, surface and peat temperatures. This analysis serves two purposes. First, it gives an indication of what the key sensitivities are in the MWM and second, it provides some initial insights into the potential sensitivity of C cycling in northern peatlands to changes in climate. In the future we plan to use MWM coupled to a surface climate model to simulate the potential affects of climate change using the output of general climate simulations as input to the coupled wetland model. **Finally, it should be repeated that in this sensitivity analysis the structure of the ecosystem does not change due to competition among plant functional types even though the range of physical conditions imposed in the sensitivity analysis is, in some cases, well outside the range that would be considered climatic and hydrologic 'niches' of the peatland plant functional plant types.** The sensitivity analyses are done for the 8 years and averaged for that period (Table 4).

To fully cover the potential climatic changes, we imposed variations from the actual water table depth of -10 cm (wetter) to +30 cm (drier) in increments of 5cm. A negative increment or a decrease in water table depth refers to a water table closer to the peat surface. The effects of the water table depth variations in moss C cycling occur through changes of moss water content, which is in turn used to calculate g_{tc} and f_{θ}. The changes in the shrub C cycling occur through variation in soil water content, which affects the stomatal conductance. Our analysis shows that a modest decrease (increase) in water table depth results in slight decreases (increases) of both GPP and autotrophic respiration. The sensitivity of autotrophic respiration for mosses is greater than that of GPP and therefore NPP increases (decreases) with a shallower (deeper) water table. The situation is reversed for shrubs. Consequently, the model favours shrub growth in a drier wetland and moss growth in a more humid one. A greater sensitivity for shrubs than for mosses to water table depth seems to indicate that moss PFT would be more stable than shrub PFT one to changes in water table depth and thereby to changes in the water balance of the ecosystem. HR is far more sensitive than the live plant derived fluxes to water table variations. Since the effective water table depth determines the partitioning between the much faster oxic decomposition rates and the slower anoxic decompositions rates, the total HR (oxic plus anoxic) increases when the water table moves deeper into the peat and decreases as the water table rises toward the peat surface. Even though the sensitivity of HR is much greater than other sensitivities, the magnitude of the fluxes derived from decomposition are relatively small, therefore the sensitivity of NEP to variations in HR is also small. The magnitude of moss NPP is much larger than other fluxes and it dictates the direction of change of NEP regardless of its low sensitivity to water table changes. In none of the simulated cases was the bog a net source of C to the atmosphere. Lafleur et al. (2005) explained the lack of an apparent relationship between water table and the observed changes in ecosystem respiration at Mer Bleue by the offset of both positive and negative factors on production and heterotrophic respiration with changes in water table.

For the temperature sensitivity analyses, we varied the mean from -2^{o}C to +5^{o}C in 1^{o}C increments. The analyses show that an increase (decrease) in temperature results in decrease (increase) in moss GPP and an increase (decrease) in moss AR. Autotrophic respiration is more sensitive to temperature change than GPP and therefore an increase (decrease) in temperature leads to a decrease (increase) in moss NPP. An increase (decrease) in temperature corresponds to an increase (decrease) in shrub NPP. The HR flux is equally responsive to temperature change: as temperature increases (decreases) the respiration increases (decreases). The changes in the fluxes with temperature are quite significant as temperature imposes an exponential impact upon C cycling. The Q_{10} relationship used to determine the temperature sensitivity of AR and HR has a higher coefficient than the Arrhenius relationship describing that of GPP; therefore, the net effect is that NEP decreases (increases) as temperature increases (decreases). These analyses show that according to MWM ombrotrophic bogs could turn into net emitter of C to the atmosphere with a persistent rise in temperature of ~ 5^{o}C.

CONCLUSION AND PROSPECTS FOR MWM

MWM captures the primary C cycling processes in northern peatlands and simulates the C exchanges between peatlands and atmosphere within the acceptable errors, when compared to tower measurements from the Mer Bleue ombrotrophic bog. Other major peatlands types include rich and poor fens, and both bogs and fens that support forest covers. MWM needs to be developed further and then evaluated for these other peatland types before it can be applied for the regional to global assessment of the interactions between climate and general peatland carbon dynamics.

Our evaluation and sensitivity analysis identifies some areas for MWM improvement to compare year-to-year dynamics. The most critical problem we discovered lies in the way evergreen shrub foliar biomass is treated. It was not anticipated that a formulation for excess leaf loss due to drought stress would be needed. However, extended periods (e.g., > 30 days) with no precipitation during the growing seasons of both 2001 and 2002 resulted in extremely dry conditions at the surface of the peatland (Roulet et al. 2007) and leaf drop from some shrubs towards the end of the summer of 2002. MWM limits the amount of foliar biomass within a specific range and currently has no capacity to shed an extra amount of litter due extended extremely dry periods. In other words, MWM lacks a function analogous to the drought stress function contained in many forest ecosystem models. Such a function would have resulted in a smaller amount of evergreen foliar biomass in the spring of 2003 and this would have reduced 2003 growing season production. Currently MWM has no interannual biomass memory. Unfortunately, our search of the literature reveals no studies reporting interannual variations in peatland vascular plant biomass. We also suspect that the moisture content of the moss does not become dry enough in years that experience drought. The supply of water to the moss is crudely modelling in MWM's present form. Once the water table drops below a certain depth – e.g. 20 to 30 cm, there is no significant capillary raise of water to the moss (Hayward and Clymo 1982). Once this occurs the moss is kept moist only by atmospheric inputs and when there are extended periods with no rain we have observed the moss becomes very desiccated. However, we currently do not simulate this desiccation well in MWM but we believe when MWM is coupled to the surface climate model we will be able to simulate plant and moss water losses much better.

The MWM also needs further development to simulate the outputs of C as CH_4 and DOC. PCARS (Frolking et al. 2002) has a crude formulation for the emission of CH_4 but it has not been widely tested. MWM does estimate anaerobic decomposition so the challenge is first estimating how much CH_4 is produced per mass of anaerobic decomposition and then emitting some of the produced CH_4 after oxidation along each of the transport pathways of diffusion, bubble flux and/or plant mediated transport. Roulet et al. (2007) and others studies conclude that DOC is a significant loss of carbon from peatlands. Some of the aerobic and anaerobic decomposition estimated in MWM has to support this net production of DOC and the simulation of this loss presents a number of challenges. First, MWM will have to be coupled to a hydrological model that gives reasonable estimates of the loss of water through runoff, and secondly the partitioning of gross decomposition among CO_2, CH_4 and net DOC export will have to be formulated to maintain continuity between the changes in C stores and fluxes. We are unaware of any studies that provide the process basis for the partitioning among the three C outputs for northern peatlands. There have been many studies of net DOC export, but none have related the export to gross DOC production or fraction of overall decomposition.

Water table depth is a key variable for peatland C cycling because it influences the spatial distribution of soil water content and subdivides the peat profile into oxic and anoxic compartments. In this stand-alone version of MWM, where there is no complementary calculations of water balance and energy balances, water table depth and soil climate are the direct inputs from field measurements. In order to investigate the response of northern peatlands to projected climate change, both water table depth and soil climate need to be simulated under the projected climate conditions. Therefore, our future plans are to couple the MWM to wetland-CLASS (Canadian Land Surface Scheme) to simulate the water table depth and soil climate. In addition, the empirical functions in this stand-alone version of MWM to simulate the moss water content will be replaced by more realistic evapotranspiration functions transferred from wetland-CLASS. After validating the coupled MWM-CLASS model against field measurements, MWM-CLASS will be ready to answer 'what-if' questions and investigate how C cycling in northern peatlands may change due to projected climate change based on the IPCC emission scenarios.

ACKKNOWLEDGEMENTS

The authors would like to thank the generous support of the Canadian Global Coupled Climate Carbon Modelling Network (CGC^{3}M) funded by the Canadian Foundation for Climate and Atmospheric Research (CFCAS) and the previous Climate Research Network of Environment Canada. The observations used in the evaluation of MWM were obtained by the support of the Mer Bleue observatory initially from a Natural Sciences and Engineering Research Council of Canada (NSERC) Strategic Grant, then from the Fluxnet Canada Research Network (CFCAS, NSERC and BIOCAP Canada), and currently by the Canadian Carbon Project (CFCAS). FSH and JW have also received graduate student support from the McGill University Global Environmental and Climate Change Research Centre (GEC3) and its predecessor the Centre for Climate and Global Change Research (C^{2}GCR). SF has been supported by grant NSF ATM-0628399.

REFERENCES

Aber, J. D. and Federer, C. A.: A generalized, lumped parameter model of photosynthesis, evapotranspiration and net primary production in temperate and boreal forest ecosystems, Oecologia, 92, 463– 474, 1992.

Arora, V.K. Simulating energy and carbon fluxes over winter wheat using coupled land surface and terrestrial ecosystem models, Agr. Forest Meteorol. 118, 21-47, 2003.

Arora, V.K. and Boer, G.J.: Fire as an interactive component of dynamic vegetation models, J. Geophys. Res. -Biogeoscience, 110, G02008, 10.1029/2005JG000042, 2005a.

Arora, V.K. and Boer, G.J.: A parameterization of leaf phenology for the terrestrial ecosystem component of climate models, Glob. Change Biol., 11, 39-59, 2005b.

Arora, V.K. and Boer, G.J.: Simulating competition and coexistence between plant functional types in a dynamic vegetation model, Earth Interactions, 10 (10), 1-30, 2006.

Ball, J.T., Woodrow, I.E. and Berry, J.A.: A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions. In: Biggens, J. (Ed.): Progress in Photosynthesis Research, vol. V, Dordrecht, Martinus Nijhoff, 221–224,1987.

Blodau, C., Roulet, N. T., Heitmann, T., Stewart, H., Beer, J., Lafleur, P., and Moore, T. R.: Belowground carbon turnover in a temperate ombrotrophic bog, Global Biogeochem. Cy., 21, GB1021, doi:10.1029/2005GB002659,2007.

Bubier, J., Moore, T.R. and Crosby, G.:Fine-scale vegetation distribution in a cool temperate peatland, Can. J. Botany, 84, 910-923,2006.

Campbell,J.D. : A simple method for determining unsaturated conductivity from moisture retention, Soil Sci., 117,311-314, 1974.

Chapin III., F.S., Woodwell, G.M., Randerson, J.T., Rastetter , E.B., Lovett, G.M. , Baldocchi, D.D., Clark, D.A., Harmon, M.E., Schimel, D. S., Valentini, R., Wirth, C., Aber, J.D., Cole, J.J., Goulden, M.L., Harden, J.W., Heimann, M., Howarth, R.W., Matson, P.A., McGuire, A.D., Melillo, J.M., Mooney, H.A., Neff, J.C., Houghton, R.A., Pace, M.L., Ryan M.G., Running, S.W., Sala, O.E., Schlesinger, W.H. and Schulze, E.-D.: Reconciling carbon-cycle concepts, terminology, and methods, Ecosystems, 9, 1041–1050, 2006.

Clapp, R. and Hornberger, G.: Empirical equations for some soil hydraulic properties, Water Resour. Res., 14, 601–604, 1978.

Clein, J. S. and Schimel, J. P.: Microbial activity of tundra and taiga soils at sub-zero temperatures, Soil Biol. Biochem., 27, 1231– 1234, 1995.

Collatz, G.J., Ball, J.T., Crivet, G., and Berry, J.A.: Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: A model that includes a laminar boundary layer, Agr. Forest Meteorol., 54, 107-136, 1991.

Collatz, G.J., Ribas-Carbo, M. and Berry, J.A.: A coupled photosynthesis-stomatal conductance model for leaves of C_4 plants, Aust. J. Plant Physiol., 19, 519-538, 1992.

Comer, N.T., Lafleur , P.M., Roulet ,N.T., Letts, M.G., Skarupa, M. and Verseghy, D.: A test of the Canadian Land Surface Scheme (CLASS) for a variety of wetland types, Atmos. Ocean, 38, 161-179, 2000.

Denman, K., Brasseur, G., et al. : Couplings Between Changes in the Climate System and Biogeochemistry, In: Solomon, S., Qin, D., Manning, M., et al (Eds.):Climate Change 2007, The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, Cambridge University Press, 1, 499-587, 2007.

Farquhar, G.D. and von Caemmerer, S.: Modelling of photosynthetic response to the environment, In: Lange, O.L., Nobel, P.S., Osmond, C.B. and Zeigler, H. (Eds.): Encyclopedia of Plant Physiology, New Series, Vol. 12B: Physiological

Plant Ecology II , Springer-Verlag, Berlin, 549–587,1982.

Farquhar, G.D., von Caemmerer, S. and Berry, J.A.: A biochemical model of photosynthesis CO_2 assimilation in leaves of C_3 plnats, Planta, 149, 78-90, 1980.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., Von Bloh, W., Brovkin, V., Cadule , P., Doney, S., Eby, M., Fung, I., Balal, G., John, J., Jones, C., Joss, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H. D., Raddatz, T., Rayner, P., Reick, C., Rockner, E., Schnitzler, K.-G., Schnur, R., Strassmann,K., Weaver,A. J., Yoshikawa,C. and Zeng,N.: Climate–carbon cycle feedback analysis: results from the C4MIP model intercomparison, J Climate,19,3337-3353,2006.

Frolking, S., Goulden, M.L., Wofsy, S.C., Fan, S-M,et al.: Modelling temporal variability in the carbon balance of a spruce/moss boreal forest, Glob. Change Biol., 2, 343– 366, 1996.

Frolking, S., Roulet, N.T., Moore, T.R., Richard, P.J.H., Lavoie, M., and Muller, S.D.: Modeling northern peatland decomposition and peat accumulation, Ecosystems, 4, 479-498, 2001.

Frolking, S., Roulet, N.T., Moore, T.R., Lafleur, P.M., Bubier, J.L., and Crill, P.M.: Modeling the seasonal and annual carbon balance of Mer Bleue bog, Ontario, Canada, Global Biogeochem. Cy., 16 (3), 10.1029/2001GB001457, 2002.

Gorham, E.: Northern peatlands: Role in the carbon budget and probable responses to global warming, Ecol. Appl., 1, 182-195, 1991.

Gorham, E.: The biogeochemistry of northern peatlands and its possible responses to global warming, In: Woodwell,G.M. and Mackenzie, F.T.(Eds.):Biotic feedbacks in the global climate system: Will the warming feed the warming? Oxford University Press, New York, 169-187, 1995.

Hagen S, Braswell B, Linder E, Frolking S, Richardson A, Hollinger D.: Statistical uncertainty of eddy flux–based estimates of gross ecosystem carbon exchange at Howland Forest, Maine. Journal of Geophysical Research-Atmospheres 111: D08S03, doi:10.1029/2005JD006154, 2006.

Harley, P.C., Tenhunen, J.D. and Lange, O.L.: Use of an analytical model to study limitations on net photosynthesis in Arbutus unedo under field conditions, Oecologia 70, 393–401,1986.

Hayward, P.M. and Clymo, R.S.: Profiles of Water Content and Pore Size in Sphagnum and Peat, and their Relation to Peat Bog Ecology, P. Roy. Soc. Lond. B. Bio., 215(1200):299-325, 1982.

Ingram, H.A.P.: Soil layers in mires: function and terminology, J. Soil Sci., 29, 224-227, 1978.

Jarvis, P.G.: The interpretation of leaf water potential and stomatal conductance found in canopies in the field, Philos. T. Roy. Soc. B., 273, 593–610,1976.

Jordan, D.B. and Ogren, W.L.: The CO_2/O_2 specificity of ribulose 1,5-bisphosphate carboxylase/oxygenase, Planta, 161(4), 308-313, 1984.

Kirschbaum, M.U.F. and Farquhar, G.D.: Temperature dependence of whole-leaf photosynthesis in *Eucalyptus pauciflora* Sieb. ex Spreng, Aust. J. Plant Physiol., **11,** 519–538,1984.

Lafleur, P., Moore, T.R., Roulet, N. T. and Frolking, S.: Dependency of ecosystem respiration in a cool temperate bog on peat temperature and water table, Ecosystems, 8, 619-629, 2005.

Lafleur, P., Roulet, N.T., Bubier, J., Frolking, S. and Moore, T.R.: Interannual variability in the peatland-atmosphere carbon dioxide exchange at an ombrotrophic bog, Global Biogeochem. Cy., 17(2), 1036, doi:10.1029/2002GB001983, 2003.

Lafleur, P.M., Roulet, N.T. and Admiral, S.: The annual cycle of CO_2 exchange at a boreal bog peatland, J. Geophys. Res. – Atmos., 106, 3071-3081, 2001.

Letts, M.G., Roulet, N.T., Comer, N.T. , Skarupa, M.R. and Verseghy, D.L.: Parameterization of peatland hydraulic properties for the Canadian Land Surface Scheme, Atmos. Ocean, 38, 141-160, 2000.

Lloyd, J., Wong, S.C., Styles, J.M., Batten D., Priddle R., Turnbull C. and McConchie C.A.: Measuring and modelling whole-tree gas exchange, Aust. J. Plant Physiol., 22, 987–1000,1995.

Medlyn, B. E., Dreyer, E., Ellsworth, D., Forstreuter, M., Harley, P.C., Kirschbaum, M.U.F., Le Roux, X., Montpied, P., Strassemeyer, J., Walcroft, A., Wang, K., Loustau, D.: Temperature response of parameters of a biochemically based model of photosynthesis, II, A review of experimental data, Plant Cell Environ., 25, 1167–1179, doi:10.1046/j.1365-3040.2002.00891.x, 2002.

Moore, T. and Basiliko, N.: Decomposition in boreal peatlands, in: Wieder, R. and Vitt,D.H. (Eds.): Boreal Peatland Ecosystems, New York, Springer, 126-143, 2006.

Moore, T.R., Bubier, J., Frolking, S., Lafleur, P. and Roulet, N.T.: Plant biomass and production and CO_2 exchange in an ombrotrophic bog, J. Ecol., 90, 25-36, 2002.

Moore, T.R., Roulet, N.T. and Waddington, M.J.: Uncertainty in predicting the effect of climatic change on the carbon cycling of Canadian peatlands, Climatic

Change, 40, 229-245, 1998.

Ouyang, B., Roulet, N.T., Lafleur, P.M. and D. Versehgy: Modelling the water table in bogs using the Canadian Land Surface Scheme (CLASS). Hydrol.Process. (in press).

Price,A. G., Dunham,K., Carleton, T. and Band, L.: Variability of water fluxes through the black spruce (Picea mariana) canopy and feather moss (Pleurozium schreberi) carpet in the boreal forest of Northern Manitoba, J Hydrol., 196, 310-323, doi:10.1016/S0022-1694(96)03233-7, 1997.

Roulet, N. T., Lafleur, P., Richard, P., Moore, T., Humphreys, E. and Bubier, J.: Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland, Glob. Change Biol., 13, 379-411, doi: 10.1111/j.1365-2486.2006.01292.x, 2007.

Ryan, M.G.: Effects of climate change on plant respiration, Ecol. Appl., 1, 157–167, 1991.
Silvola, J.: Combined effects of varying water content and CO_2 concentration on photosynthesis in Sphagnum fuscum, Holarctic Ecol. 13, 224-228, 1990.

Smith E.: The influence of light and carbon dioxide on photosynthesis, General Physiology 20, 807-830, 1937.

Tenhunen, J.D.,Weber, J.A., Yocum, C.S. and Gates, D.M.: Development of a photosynthesis model with an emphasis on ecological application, II, Analysis of a data set describing the P_m surface, Oecologia, 26, 101-109, 1976.

Thornton, P., Lamarque, J.-F., Rosenbloom, N. and Mahowald, N.: Influence of carbon-nitrogen cycle coupling on land model response to CO_2 fertilization and climate variability, Global Biogeochem. Cy., 21: GB4018, doi:10.1029/2006GB002868, 2007.

Turunen, J., Tomppo, E., Tolonen, K. and Reinikainen, A.: Estimating carbon accumulation rates of undrained mires in Finland - application to boreal and subarctic regions, Holocene, 12, 69-80, 2002.

Williams, T.G. and Flanagan, L.B.: Measuring and modelling environmental influences on photosynthetic gas exchange in Sphagnum and Pleurozium, Plant Cell Environ., 21, 555-564, doi:10.1046/j.1365-3040.1998.00292.x, 1998.

TABLES

Parameter	Value	Units	Description	Reference/Source
Values for Model Parameters at 25C				
J_{max}:V_{max}	1.67	-	ratio	Medlyn et al. 2002
mosses				
V_{cmax25}	6	umol $m^{-2}s^{-1}$	max carboxylation rate (spring)	Williams & Flanagan 1998
	14	umol $m^{-2}s^{-1}$	max carboxylation rate (summer)	idem
	7	umol $m^{-2}s^{-1}$	max carboxylation rate (autumn)	idem
R_{d25}	0.946	umol $m^{-2}s^{-1}$	dark respiration rate	Harley et al. 1989
shrubs				
V_{cmax25}	17	umol $m^{-2}s^{-1}$	max carboxylation rate	N.T. Roulet unpublished
Site specific				
frac	48.7	%	biomass to carbon ratio	T.R. Moore unpublished
B_{moss}	144	g dry biomass m^{-2}	moss capitula biomass	Moore et al. 2002
$B_{min\ foliar}$	175	g dry biomass m^{-2}	min shrub foliar biomass	idem
$B_{max\ foliar}$	600	g dry biomass m^{-2}	max shrub foliar biomass	idem
B_{stem}	0.003	m^3m^{-2}	shrub sapwood volume	idem
PD_0	4	m	initial peat depth	Roulet 2007
Others				
$\exists_{lim}$	0.04/0.15	-	residual soil-water content in fibric/hemic peat	Letts et al. 2000
$\exists_{p}$	0.93/0.88	-	soil porosity in fibric/hemic peat	idem
$+_{sat}$	0.0103/0.0102	m	soil matric potential at saturation in fibric/hemic peat	idem
b	2.7/4.0	-	soil texture parameter in fibric/hemic peat	idem
$\exists_{maxcap}$	15	g H2O g dry $biomass^{-1}$	maximum holding capacity of moss	Silvola 1990
$\exists_{mincap}$	5	g H2O g dry $biomass^{-1}$	minimum interception capacity of moss	Price et al. 1997
k_d	1	%	water loss rate in capitulum	Frolking et al. 1996
k_o	0.05/0.2	y^{-1}	intial decomposition rate for moss/shrub	T.R. Moore unpublished

Table 1: Model parameters and initialization

Table 2: Observed (Obs.), simulated (Sim.), and the difference between observed and simulated (Δ) annual NEP, GPP and ER for 8 years for the Mer Bleue peatland.

	NEP			GPP					ER							NPP		
Year	Obs.	Sim.	D	Obs.	Sim.	D	moss[1]	shrub[1]	Obs.	Sim.	D	moss[1]	shrub[1]	oxic HR[1]	anoxic HR[1]	Sim.	moss[1]	shrub[1]
1999	65	1	-64	646	624	-22	0.34	0.66	-582	-623	-36	0.27	0.65	0.08	<0.01	52	0.82	0.16
2000	32	78	46	463	628	165	0.39	0.61	-431	-550	-119	0.27	0.65	0.08	<0.01	126	0.79	0.21
2001	2	39	37	543	662	119	0.33	0.67	-541	-623	-81	0.26	0.65	0.08	<0.01	93	0.61	0.39
2002	13	35	22	511	647	136	0.38	0.62	-498	-612	-116	0.27	0.64	0.09	<0.01	91	0.89	0.11
2003	15	85	70	495	667	172	0.36	0.60	-480	-582	-102	0.28	0.63	0.08	<0.01	136	0.58	0.42
2004	115	133	18	683	713	30	0.36	0.64	-568	-580	-12	0.28	0.63	0.08	<0.01	181	0.52	0.48
2005	91	101	10	668	710	42	0.34	0.66	-598	-609	-11	0.28	0.64	0.08	<0.01	151	0.49	0.51
2006	147	99	-48	772	704	-68	0.34	0.66	-625	-604	20	0.27	0.65	0.08	<0.01	147	0.56	0.44
Mean	60	71	11	598	669	72	0.36	0.60	-540	-598	-57	0.27	0.64	0.08	<0.01	122	0.62	0.38
Std. Dev.	53	43	-	110	36	-	0.02	0.02	66	25	-	0.01	0.01	0.00	<0.01	41	0.37	0.16

[1] contribution

Table 3: The ranking of the relative patterns on water table and temperatures for the 8 years of comparison between the observed and simulated peatland carbon dynamics.

	1999	2000	2001	2002	2003	2004	2005	2006
temperature[1]	1	8	4	6	5	7	2	3
water table[2]	1	7	2	3	4	6	5	8
NEP[3]	8	5	6	7	4	1	2	3
GPP[3]	8	7	5	6	4	1	2	3
ER[3]	2	8	1	3	6	7	4	5

[1] temperature ranking: 1 = warmest, 8 = coldest

[2] water table ranking: 1 = shallowest, 8 = deepest

[3] NEP, GPP, and ER ranking: 1 = largest, 8 = smallest.

Tale 4: The sensitivity of simulated GPP, autotrophic respiration (AR), NPP and oxic and anoxic heterotrophic respiration (HR) expressed in percent change relative to the baseline simulation (observed environmental variables). A negative sign indicates a decrease relative to the baseline while a positive sign indicates an increase.

	moss			**shrub**					
	GPP	AR	NPP	GPP	AR	NPP	NEP	Oxic HR	Anoxic HR
Base line ($gC/m^2/y$)	**237.82**	**-166.48**	**71.34**	**431.52**	**-415.72**	**15.80**	**68.79**	**-16.24**	**-2.11**
hwtd(-10cm)	-0.22	-3.44	+7.28	-0.49	-0.19	-8.38	+11.34	-40.10	+122.25
hwtd(-5cm)	-0.09	-1.36	+2.86	-0.24	-0.09	-4.15	+5.56	-19.75	+36.68
hwtd(+5cm)	+0.06	+0.82	-1.74	+0.24	-0.09	+8.92	-3.55	+17.35	-9.81
hwtd(+10cm)	+0.08	+1.22	-2.58	+0.45	+0.18	+7.4	-8.53	+34.07	-16.05
hwtd(+15cm)	+0.09	+1.33	-2.82	+0.67	+0.26	+11.28	-11.73	+50.95	-20.65
hwtd(+20cm)	+0.09	+1.34	-2.85	+0.91	+0.37	+15.03	-14.90	+68.12	-22.21
airT(-2)	+2.11	-15.19	+42.46	-12.11	-17.16	+120.7	+51.76	-15.61	-12.89
airT(-1)	+1.18	-7.77	+22.03	-5.72	-8.61	+70.41	+21.76	-7.74	-6.66
airT(+1)	-1.38	+8.09	-23.48	+4.92	+8.84	-98.09	-15.08	+7.60	+7.16
airT(+2)	-3.04	+16.47	-48.59	+9.22	+18.06	-223.36	-41.68	+15.48	+14.82
airT(+3)	-4.59	+25.12	-73.94	+11.87	+27.54	-400.47	-78.67	+23.83	+23.03
airT(+5)	-8.32	+43.04	-128.15	+14.79	+48.15	-863.07	-174.52	+42.28	+41.26

Figure 1: The time series of hourly measured (blue dashed line) and simulated (red solid line) GPP for 1999-2006.

Figure 2: The scatter plot of observed and simulated daily GPP and ER for 1999-2006. The sold black line indicates the 1:1 line and the dashed line is the best fit relationship between the observations and the simulated GPP and ER.

Figure 3: The time series of hourly measured (blue dashed line) and simulated (red solid line) ER for 1999-2006.

Figure 4: The time series of hourly measured (blue dashed line) and simulated (red solid line) NEP for 1999-2006.

Figure 5: The scatter plot of observed and simulated daily GPP and ER for 1999-2006. The sold black line indicates the 1:1 line and the dashed line is the best fit relationship between the observations and the simulated NEP.

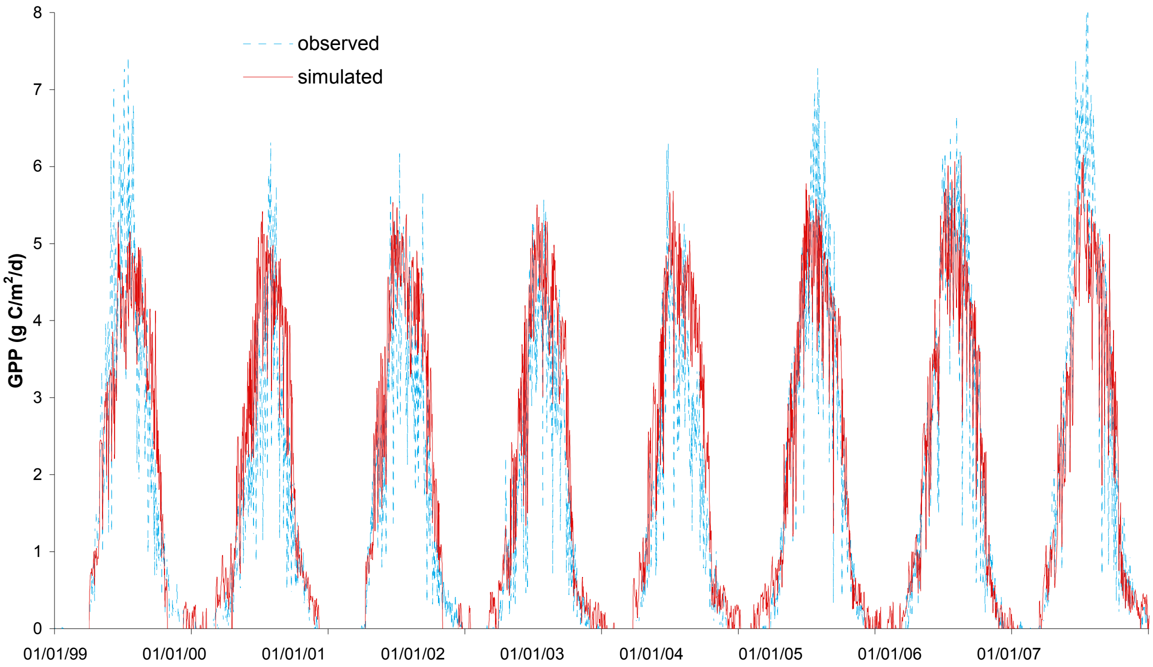


Figure1

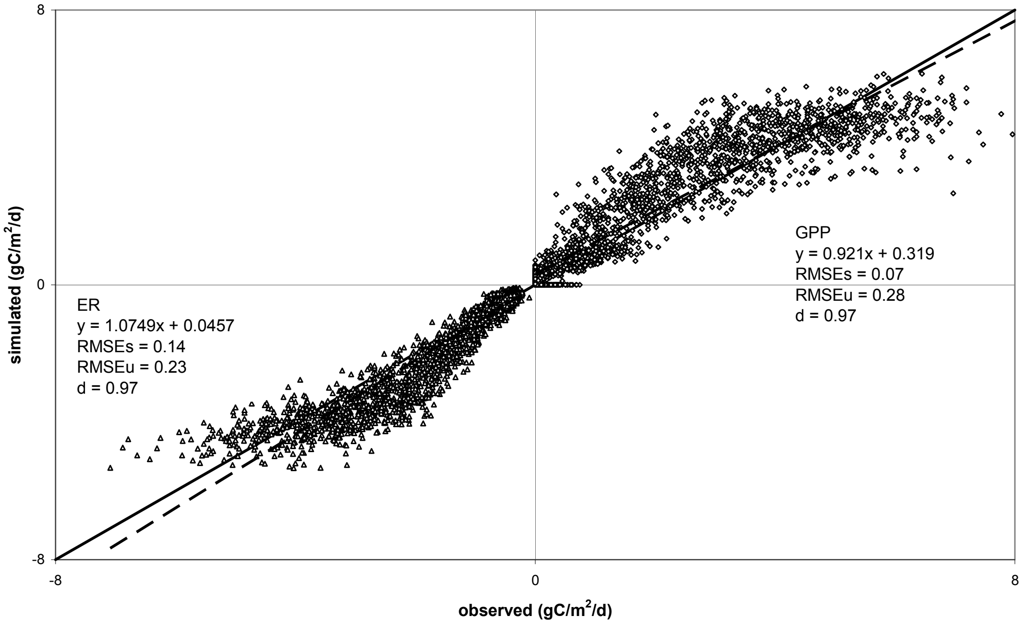


Figure2

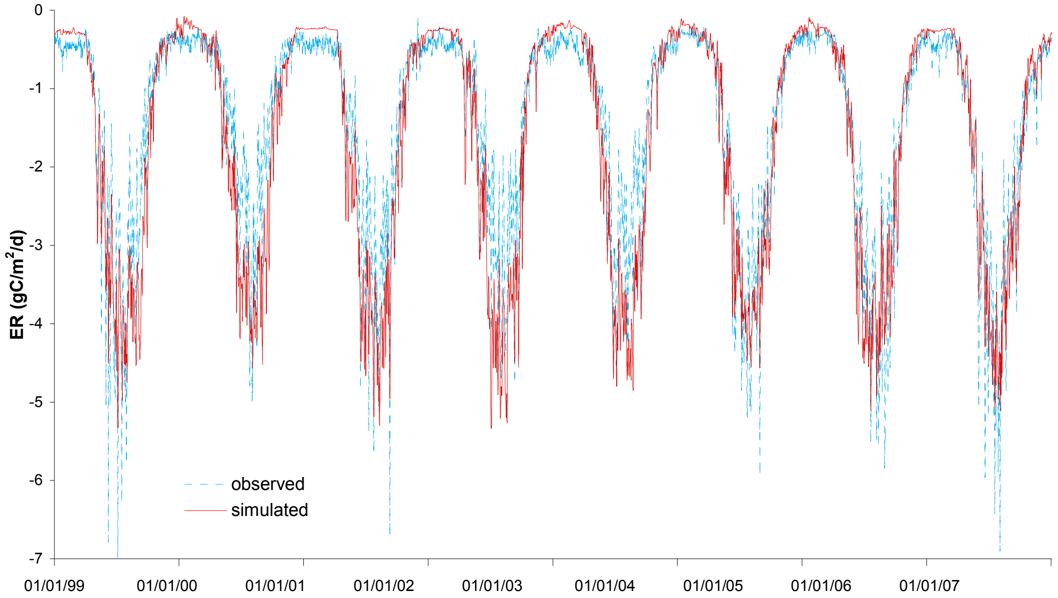


Figure 3

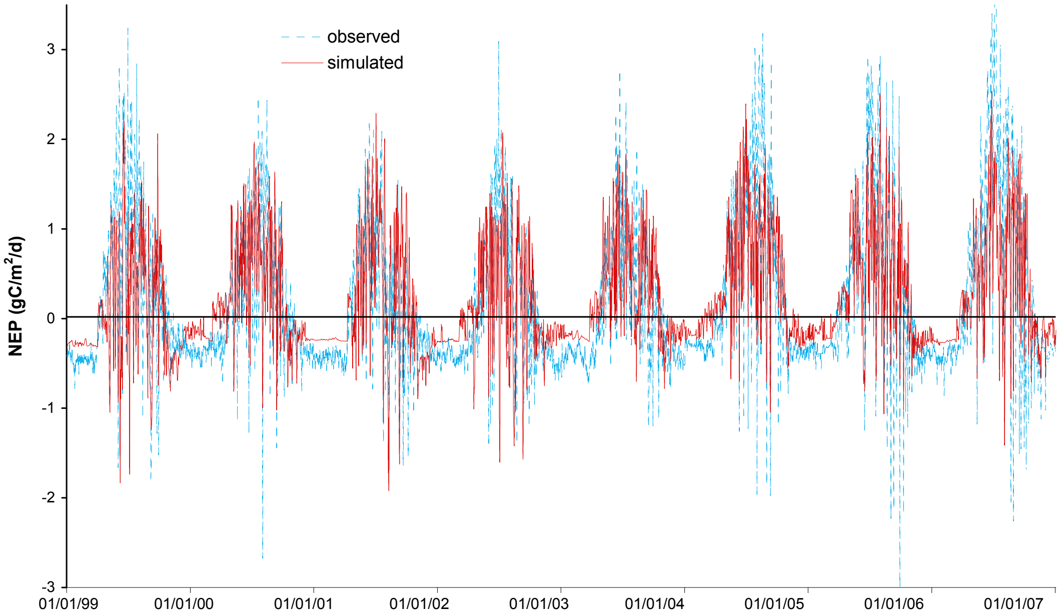


Figure4

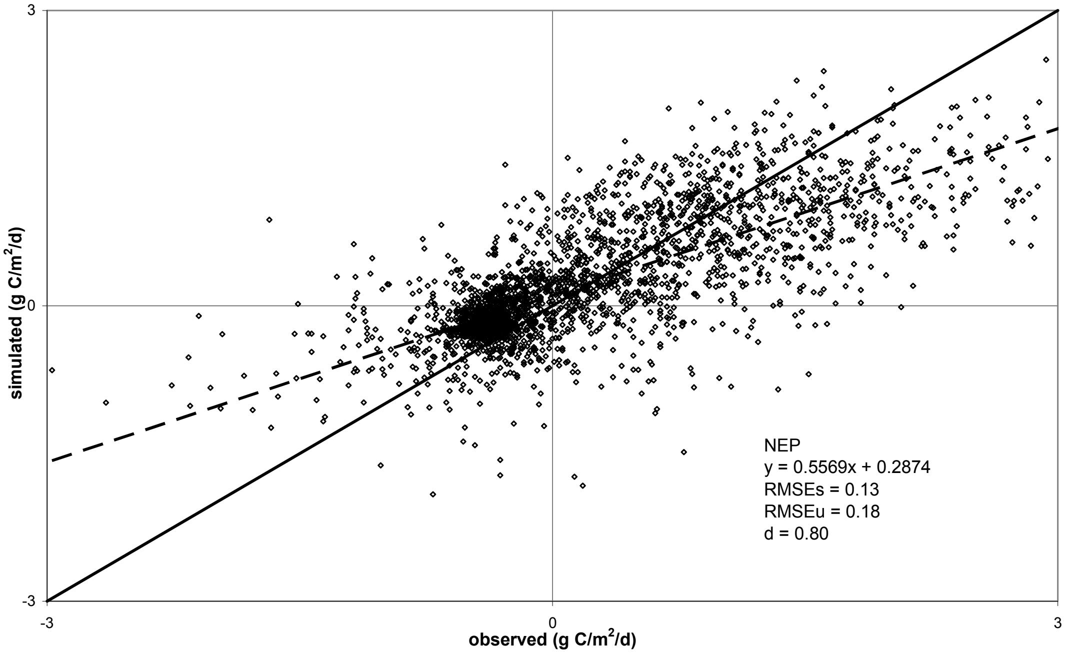

3
0
-3
-3
0
3
simulated (g C/m²/d)
observed (g C/m²/d)
NEP
y = 0.5569x + 0.2874
RMSEs = 0.13
RMSEu = 0.18
d = 0.80

Figure 5