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A regional modelling approach

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Peatland dynamics in response to past and potential future climate change

Peatland dynamics in response to past and potential future climate change

a regional modelling approach

Nitin Chaudhary

DOCTORAL DISSERTATION

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To be defended at Världen, Geocentrum I, Sölvegatan 12, Lund

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Faculty opponent

Dr. Mathew Williams

Global Change Research Institute

University of Edinburgh, UK

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Abstract

The majority of the northern peatlands developed during the Holocene as a result of a positive mass balance between net primary productivity (NPP) and heterotrophic decomposition rates. Over that time they have sequestered a huge amount of carbon in terrestrial ecosystems. A significant proportion of these areas also coincides with areas underlain with permafrost and shows a diverse range of peat accumulation patterns. Thus, for predicting and understanding the long-term evolution of peatland carbon stocks across the pan-Arctic, mechanistic representations of both peatland and permafrost dynamics are needed in the modelling framework. In this thesis, a novel implementation of dynamic multi-layer peatland and permafrost dynamics in the individual- and patch- based dynamic vegetation and ecosystem model (LPJ-GUESS) is described. The major emphasis of this work goes into enhancing the current understanding of the processes involved in the long-term peat accumulation and its internal dynamics, including how these systems are influenced by small-scale heterogeneity, vegetation dynamics and interactions with underlying permafrost. A simple two-dimensional microtopographical (2-DMT) model was also developed to address the established hypotheses concerning stability, behaviour and transformation of these microstructures and the effects of this small-scale heterogeneity on the coupled dynamics of vegetation, hydrology and peat accumulation. LPJ-GUESS was calibrated and validated using data from a mire in Stordalen, northern Sweden, and evaluated using data from multiple sites in Scandinavia and from Mer Bleue, Canada. It was subsequently applied across the pan-Arctic to advance the existing knowledge on carbon accumulation rates at different spatial and temporal scales, and also to demonstrate the potential implications of current warming on these climate sensitive ecosystems. Both of the models developed in this thesis performed satisfactorily when confronted with experimental data.

LPJ-GUESS is quite robust in capturing peat accumulation and permafrost dynamics including reasonable vegetation and hydrological conditions at temporal and spatial scales across various climate gradients. The simulations improved our knowledge of peatland functioning in the past, present and future. It was found that Stordalen mire will continue to accumulate carbon in the coming decades but later will turn into a carbon source. It was also found that permafrost-free regions that are predicted to experience reduced rates of precipitation may lose significant amount of carbon in the future due to reductions in soil moisture. Conversely, peatlands currently underlain with permafrost could gain carbon due to an initial increase in soil moisture as a result of permafrost thawing. My modelling results also suggest that peatlands can show diverse range of behaviour with alternative compositional and structural dynamics depending on the initial topographical, climatic conditions, and plant characteristics, therefore, it will be challenging to represent such dynamics in current Earth System Models (ESMs). With the inclusion of aforementioned processes, LPJ-GUESS has now become quite robust. The resultant model can now be coupled with ESM where it can address issues related to peatland-mediated biogeochemical and biophysical feedbacks to climate change in the Arctic and globally.

Key words: Peatlands, permafrost, carbon accumulation, microtopography, LPJ-GUESS, Earth system models

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Nitin

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a regional modelling approach

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A doctoral thesis at a university in Sweden is produced either as monograph or a collection of papers. In the latter case, the introductory part constitutes the formal thesis, which summarises the accompanying papers already published or manuscripts at various stages (in press, submitted or in preparation).

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This thesis is dedicated to the memory of my late father

One must have chaos in oneself to give birth to a dancing star

Contents

List of papers

I. **Chaudhary, N.,** Miller, P. A., and Smith, B.: Modelling Holocene peatland dynamics with an individual-based dynamic vegetation model, Biogeosciences Discussion, doi:10.5194/bg-2016-319, in review, 2016.

II. **Chaudhary, N.,** Miller, P. A., and Smith, B.: Modelling past, present and future carbon accumulation rates and permafrost distribution across the pan-Arctic, Biogeosciences Discussion, doi:10.5194/bg-2017-34, in review, 2017.

III. **Chaudhary, N.,** Miller, P. A., and Smith, B.: Biotic and abiotic drivers of peatland growth and microtopography: a model demonstration. ***Submitted to Ecosystems***

IV. Ekici, A., Chadburn, S., **Chaudhary, N.,** Hajdu, L. H., Marmy, A., Peng, S., Boike, J., Burke, E., Friend, A. D., Hauck, C., Krinner, G., Langer, M., Miller, P. A., and Beer, C.: Site-level model intercomparison of high latitude and high altitude soil thermal dynamics in tundra and barren landscapes, The Cryosphere, 9, 1343-1361, doi:10.5194/tc-9-1343-2015, 2015.

List of Contribution

I. NC implemented peatland dynamics in the customised Arctic version of LPJ-GUESS, designed the model study with guidance from the other authors, and performed the simulations. NC led the writing with all authors contributing.

II. NC designed the model study and performed the model simulations and analysis. NC led the writing with all authors contributing.

III. NC developed a two-dimensional microtopographical model based on a concept developed in discussion among the authors and performed the simulations. NC led the writing with all authors contributing.

IV. The paper is a model intercomparison study carried out as a community effort with the aim of refining the representation of soil physical processes in cold region models. NC performed and contributed the LPJ-GUESS model simulations and provided input to the manuscript.

Abbreviations

ALD	Active layer depth
AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
aWTP	Annual water table position
BP	Before present
CO_2	Carbon dioxide
CH_4	Methane
DGVM	Dynamic global vegetation model
DOC	Dissolved organic carbon
ESM	Earth System Model
GCM	Global Climate Model
GHGs	Greenhouse gases
Gr	Graminoids
HSS	High summergreen shrub
HTM	Holocene Thermal Maximum
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
Kyr	Thousand years
LARCA	Long-term "apparent" rate of carbon accumulation
LPJ-GUESS	Lund-Potsdam-Jena General Ecosystem Simulator
LSE	Low evergreen shrub
LSS	Low summergreen shrub
M	Mosses
N	Nitrogen
NPP	Net primary productivity
NEE	Net ecosystem exchange
PFT	Plant functional type
PgC	Petagram Carbon
RCP	Representative concentration pathways
S	Shrubs
TgC	Teragram Carbon
TOPMODEL	TOPography based hydrological MODEL
WTP	Water table position
2-DMT	Two-dimensional microtopographical model
°C	Degree Celsius
°N	Degree North

Abstract

The majority of the northern peatlands developed during the Holocene as a result of a positive mass balance between net primary productivity (NPP) and heterotrophic decomposition rates. Over that time they have sequestered a huge amount of carbon in terrestrial ecosystems. A significant proportion of these areas also coincides with areas underlain with permafrost and shows a diverse range of peat accumulation patterns. Thus, for predicting and understanding the long-term evolution of peatland carbon stocks across the pan-Arctic, mechanistic representations of both peatland and permafrost dynamics are needed in the modelling framework. In this thesis, a novel implementation of dynamic multi-layer peatland and permafrost dynamics in the individual- and patch- based dynamic vegetation and ecosystem model (LPJ-GUESS) is described. The major emphasis of this work goes into enhancing the current understanding of the processes involved in the long-term peat accumulation and its internal dynamics, including how these systems are influenced by small-scale heterogeneity, vegetation dynamics and interactions with underlying permafrost. A simple two-dimensional microtopographical (2-DMT) model was also developed to address the established hypotheses concerning stability, behaviour and transformation of these microstructures and the effects of this small-scale heterogeneity on the coupled dynamics of vegetation, hydrology and peat accumulation. LPJ-GUESS was calibrated and validated using data from a mire in Stordalen, northern Sweden, and evaluated using data from multiple sites in Scandinavia and from Mer Bleue, Canada. It was subsequently applied across the pan-Arctic to advance the existing knowledge on carbon accumulation rates at different spatial and temporal scales, and also to demonstrate the potential implications of current warming on these climate sensitive ecosystems. Both of the models developed in this thesis performed satisfactorily when confronted with experimental data.

LPJ-GUESS is quite robust in capturing peat accumulation and permafrost dynamics including reasonable vegetation and hydrological conditions at temporal and spatial scales across various climate gradients. The simulations improved our knowledge of peatland functioning in the past, present and future. It was found that Stordalen mire will continue to accumulate carbon in the coming decades but later will turn into a carbon source. It was also found that permafrost-free regions that are predicted to experience reduced rates of precipitation may lose significant amount of carbon in the future due to reductions in soil moisture. Conversely, peatlands currently underlain with permafrost could gain carbon due to an initial increase in soil moisture as a result of permafrost thawing. My modelling results also suggest that peatlands can show diverse range of behaviour with alternative compositional and structural dynamics depending on the initial topographical and climatic conditions, and plant characteristics, therefore, it will be challenging to represent such dynamics in current Earth System Models (ESMs). With the inclusion of aforementioned processes, LPJ-GUESS has now become quite robust. The resultant model can now be coupled with

ESM where it can address issues related to peatland-mediated biogeochemical and biophysical feedbacks to climate change in the Arctic and globally.

Sammanfattning

En majoritet av de nordliga torvmarkerna utvecklades under holocen som ett resultat av en positiv massbalans mellan nettoprimärproduktion och heterotrofa nedbrytningshastigheter. Sedan dess har de lagrat stora mängder kol i terrestra ekosystem. En betydande del av dessa områden sammanfaller också med regioner med underliggande permafrost och uppvisar olika ackumulationsmönster av torv. Således, för att kunna förutse och förstå den långsiktiga utvecklingen av kollagret i torvmark i Arktiska områden, är det nödvändigt att använda mekanistiska framställningar av både torvmark och permafrost i modellering. I den här avhandlingen beskrivs en ny dynamisk flerskiktsimplementering av torvmarker och permafrostdynamik i den individ- och patchbaserade dynamiska vegetations- och ekosystemmodellen LPJ-GUESS. Syftet med studierna i avhandlingen är att förbättra förståelsen av de processer som påverkar långsiktig torvackumulering och dess inre dynamik samt att inkludera hur dessa system påverkas av småskalig heterogenitet, vegetationsdynamik och interaktion med underliggande permafrost. En enkel tvådimensionell mikrotopografisk modell har också tagits fram för att undersöka etablerade hypoteser rörande stabilitet, beteende och transformation av dessa mikrostrukturer och effekter av denna småskaliga heterogenitet på kopplad dynamisk vegetation, hydrologi och torvackumulering. LPJ-GUESS kalibrerades och validerades med data från en myr i Stordalen i norra Sverige och utvärderades med data från flera platser i Skandinavien och Mer Bleue i Kanada. Modellen tillämpades sedan på regional nivå för att förbättra kunskapen om kolinlagringshastigheter för olika rums- och tidsupplösningar samt för att demonstrera potentiella följder av nuvarande uppvärmning på dessa klimatkänsliga ekosystem. Båda modellerna som utvecklades i den här avhandlingen fungerade tillfredsställande vid jämförelser med experimentella data.

LPJ-GUESS är tämligen robust på att beskriva torvackumulering och permafrostdynamik med rimliga vegetations- och hydrologiska förhållanden för tids- och rumsupplösningar för olika klimatgradienter. Simuleringarna förbättrade vår kunskap om hur torvmarken utvecklades i det förflutna men också hur det utvecklas idag och kan komma att utvecklas i framtiden. Det visade sig att myren i Stordalen kommer att fortsätta att ackumulera kol de kommande årtionderna men senare kommer att övergå till en kolkälla. Det visade sig också att permafrostfria regioner som förutses erhålla reducerad mängd av nederbörd kan komma att förlora en signifikant mängd kol i framtiden till följd av minskad markfukt, medan torvmark med underliggande permafrost kan öka kolinlagringen på grund av en initial ökning i markfukt till följd av permafrostupptining, vilket undertrycker nedbrytning och förhöjer växtproduktion. Våra modelleringsresultat antyder även att torvmark kan uppvisa olika beteende med alternativ sammansättning och strukturell dynamik

beroende på initiala topografiska- och klimatologiska förhållanden, växtegenskaperna och det kommer i allmänhet att bli en utmaning att inkludera dem i nuvarande ESM:s. Dock så är LPJ-GUESS redo att användas i ESM:s i sin nuvarande form där den kan hantera problem relaterade till biogeokemiska och biofysikaliska återkopplingar till klimatförändringar i Arktis och globalt.

सार

जायदातर उत्तरी पीटलैंड का अधकिांश भाग होलोसीन के दौरान वकिसति होने का मुख्य कारण प्राथमकि उत्पादकता और अपघटन दर के बीच सकारात्मक द्रव्यमान संतुलन होना है । समय के साथ-साथ इन स्थलीय पारस्थितिकिी तंत्र में बहुत अधकि कार्बन इकठ्ठा हो गया । इन जगहों पर ठंडे बर्फ़ीली मैदान भी है और उसके परणिामस्वरूप वभिन्नि प्रकार के पीट पैटर्न दीखते है । पैन-आर्कटकि और क्षेत्रीय स्तर पर पीटलैंड कार्बन स्टॉक के व्यवहार की भवष्यिवाणी के लिए मॉडलगि ढांचे में इन दोनों वशिषताओं का प्रतनिधित्वि करना आवश्यक है। इस थीससि में, इंडविजुिअल- और पैच-आधारति गतशिील वनस्पत मिॉडल (LPJ-GUESS) में गतशिील बहु-पीट परत और परमफ्रॉस्ट का एक नया कार्यान्वयन वर्णति है। इस काम का मुख्य जोर दीर्घकालकि पीट संचय और इसकी आंतरकि गतशिीलता में शामलि प्रक्रयिाओं को समझने में और कैसे ये सस्टिम छोटे पैमाने पर ववधिता और वनस्पत किी गतशिीलता और अंतर्नहिति परमप्रॉस्ट के प्रभाव से बदलता है। स्थरिता, व्यवहार और इन माइक्रो स्ट्रक्चर के परवरि्तन और इस छोटे पैमाने पर ववधिता के प्रभाव और वनस्पत-जिल वज्ञिान और पीट संचय के युग्मति गतशिील के बारे में परकिल्पना को संबोधति करने के लिए एक सरल दो आयामी सूक्ष्म स्थलाकृतकि (२-डीएमटी/2-DMT) मॉडल भी वकिसति कयाि गया था। मॉडल को कैलब्रिेटेड और मूल्यांकन स्टॉर्डेन में कयाि गया और स्कैंडनिवयाि और मैर बलि्यू, कनाडा में कई साइटों पर परीक्षण कयाि गया। यह क्षेत्रीय पैमाने पर लागू कयाि गया था जो मौजूदा स्थानकि ज्ञान को वभिन्नि स्थानकि और सैद्धांतकि स्तरों पर कार्बन संचय दर पर पूरक करने के लिए भी लागू कयाि गया था जो इन जलवायु संवेदनशील पारस्थितिकि तंत्रों पर वर्तमान गर्मी के संभावति प्रभावों का भी प्रदर्शन करता है। प्रायोगकि डेटा के सामने आने पर इस थीससि में वकिसति कएि गए दोनों मॉडल संतोषजनक तरीके से प्रदर्शन करते हैं।

लपज-गेस (LPJ-GUESS) वभिन्नि जैव ग्रडियिंट्स में लौककि और स्थानकि स्तर पर उचति वनस्पत और जल वज्ञिान स्थतियिों सहति पीट संचय और परमफ्रॉस्ट गतशिीलता को कैप्चर करने में काफी मजबूत है। समिुलेशन ने पछिले, वर्तमान और भवष्यि में पीटलैंड के कामकाज के हमारे ज्ञान में सुधार कयाि है। यह पाया गया है की स्टोर्डलेन (Stordalen) आने वाले दशकों में

कार्बन जमा करना जारी रखेगा लेकिनि बाद में कार्बन स्रोत बन जाएगा। यह भी पाया गया की मटिटी की नमी में कटौती के कारण पर्माफ्रॉस्ट मुक्त क्षेत्रों को वर्षा की कम दरों के अनुभव होने से भविष्य में कार्बन की महत्वपूर्ण मात्रा में कमी आ सकती है। इसके विपरीत, वर्तमान में पर्माफ्रॉस्ट पीट्लैंड पर्माफ्रॉस्ट थोविंग के परणािमस्वरूप मट्टिी की नमी में प्रारंभिकि वृद्धि के कारण कार्बन प्राप्त कर सकते हैं। नमी की स्थिति में यह प्रारंभिकि वृद्धि अपघटन दर को दबा देती है और पौधों के उत्पादन को बढ़ाती है। मेरे मॉडलिंग परणािम यह भी सुझाव देते हैं कि पिटलैंड प्रारंभिकि स्थलाकृतिकि, जलवायु परस्थितियिों और पौधे की विशेषताओं के आधार पर वैकल्पिकि रचनात्मक और संरचनात्मक गतशिीलता के साथ विभिन्नि प्रकार के व्यवहार को दखिा सकते हैं, इसलिए वर्तमान पृथ्वी ससि्टम मॉडल (ESM) में ऐसी गतशिीलता का प्रतनिधित्वि करना चुनौतीपूर्ण होगा । उपरोक्त प्रक्रयािओं को शामलि करने के साथ, एलपीजे-ग्यूस अब काफी मजबूत हो गया है। परणािमी मॉडल को अब ईएसएम (ESM) के साथ जोड़ा जा सकता है, जहां यह आर्कटिकि और विश्वि स्तर पर जलवायु परविर्तन के लिए पीटलैंड-मध्यस्थता वाले बायोगाइकेमकिल और बायोफजिकिल फीडबैक से संबंधति मुद्दों को हल कर सकता है।

1. Introduction

Northern peatlands share many features of upland and wetland ecosystems, in general, but exhibit some unique characteristics such as a shallow water table, anoxic biogeochemistry, carbon-rich soils and spatial heterogeneity influencing vegetation cover at micro (1–10 m) to macro (> 10^4 m) scales. It is a store house of recalcitrant dead organic mass mainly composed of *Sphagnum* species (Clymo, 1991). The dead organic matter is accumulated when the litter production is greater than the total peat decay. Because of this persistent sink, peatlands have stored large amounts of organic carbon, *i.e.*, approximately 30% of the present-day soil carbon pool (Fig. 1) and are considered one of the biggest carbon storage in the terrestrial ecosystem (ca. 350–500 PgC) (Gorham, 1991; Turunen et al., 2001; Yu et al., 2010), equivalent to earth's vegetation (ca. 550 PgC) and almost half of the atmospheric carbon dioxide (CO_2) (ca. 750 PgC) (IPCC, 2013).

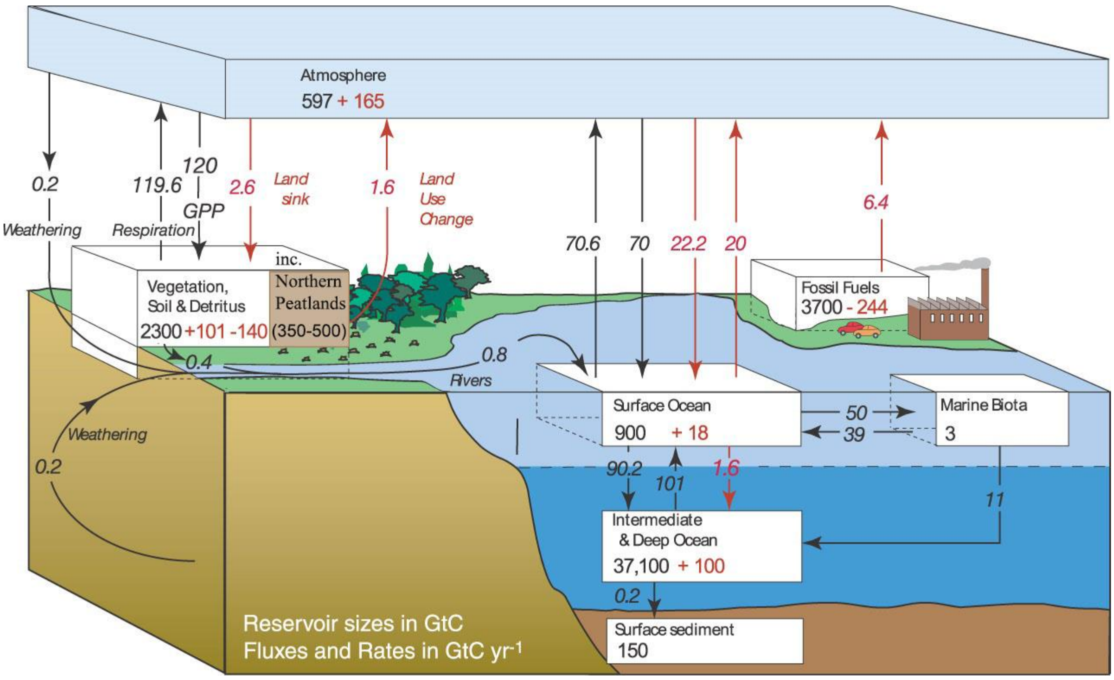

Figure 1 The global carbon cycle of the 1990s showing the carbon pools (PgC) and the annual carbon fluxes (PgC y^{-1}). The red lines representing pre-industrial and black lines signify anthropogenic carbon fluxes and pools (Modified from IPCC, AR4, Chapter 7, Figure 3, page 515).

Peatlands are also a major source of methane (CH_4) contributing significantly to the greenhouse effect (IPCC 2013). The global peatland expansion and contraction are well correlated with past fluctuations in the atmospheric CH_4 concentration, hence facilitate in identifying the factors responsible for the peatland formation and development (MacDonald et al., 2006). As per the proxy dataset, peatlands started forming since the last glacial maximum around 20 kyr BP (20 thousand years before present: 1950) but the majority of them were initiated during the mid-Holocene period around 8–12 kyr BP covering large areas from the north to south latitudes (Yu et al., 2010). More than 85% of these peat–rich complexes are present in northern latitude areas (between 45-75 °N) and a significant fraction of them are also underlain by frozen ground surface (continuous and discontinuous frozen ground), categorising peatlands into permafrost and non-permafrost peatlands (Tarnocai et al., 2009).

The current climate debate is mainly focused on the likely path the global average atmospheric CO_2 concentration might follow and its potential consequences on the global surface temperature (Le Quéré et al., 2016). The most optimistic future climate projections report at least 1.5–2 °C warming even if the CO_2 level stabilises (Fig. 2) (Peters et al., 2013; Friedlingstein et al., 2014). It is also predicted that the projected warming would be amplified in the northern high-latitude regions due to the associated biophysical and biogeochemical feedbacks and these regions may experience a warming of more than 5 °C (Arneth et al., 2010; Bathiany et al., 2010; Zhang et al., 2014). With this magnitude of warming, it is expected that the huge pristine peat-rich landscapes from Eurasia to North America would experience a dramatic upheaval sufficient to alter their existing carbon sink capacity (Christensen et al., 2004; Ise et al., 2008; Fan et al., 2013).

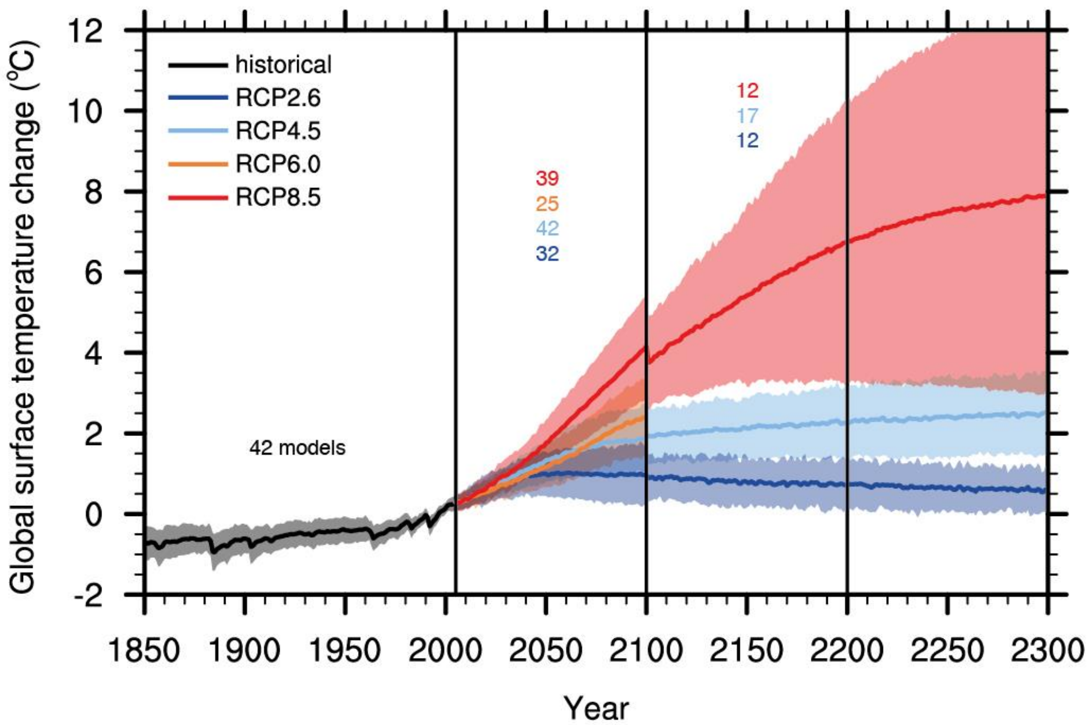

Figure 2 Warming projections (°C) under different emission scenarios. Zero is set at the average of 1986-2005 levels (IPCC AR5, Chapter 12, Figure 5, page 1054. The figure is reproduced with the kind permission of IPCC.

The first signs of these alterations have been noticed on the fringes and sensitive places across the modern peatland landscape (Yu et al., 2009; Loisel and Yu, 2013). In permafrost peatlands, recent evidences show an increase in the number of thermokarst lakes, peat subsidence, peat collapse and deeper active layer depth (ALD) due to higher atmospheric temperature leading to a complete shift from a recalcitrant moss-dominated vegetation community to dominance of non-peat-forming vegetation cover in many regions (Christensen et al., 2004; Johansson et al., 2006; Åkerman and Johansson, 2008; Swindles et al., 2015). On the other hand, the non-permafrost peatlands have been experiencing a drastic shift in their hydrological balance as a result of higher evapotranspiration (Lund et al., 2012). This accelerated rate of evapotranspiration under limited moisture conditions would potentially alter the internal biogeochemical processes of these ecosystems. Studies have also shown that higher temperature and limited moisture availability have deepened the water table, encouraging shrubs and trees to grow and modifying their present rate of carbon sequestration capacity (Sturm et al., 2005; Loranty and Goetz, 2012), a phenomenon widely reported across the pan-Arctic.

Conversely, large proportion of these peatland areas may also benefit from this accelerated rate of warming, higher precipitation rate, longer growing season and enhanced atmospheric CO_2 level (Lund et al., 2010; Charman et al., 2013). Warmer, longer growing seasons and elevated CO_2 promote plant productivity and high moisture level (driven by permafrost thaw or higher precipitation) compensates the temperature-driven decomposition rate (Yu, 2006). The combined effect of these factors would result in a substantive increase in peat accumulation rate. Currently, certain areas that were cold and perennially frozen with low carbon accumulation have been noticing a three- and four- fold increase in their productivity (Hinzman et al., 2005; Klein et al., 2013; Loisel and Yu, 2013). In future, their sink capacity may be further enhanced (Klein et al., 2013; Loisel and Yu, 2013) offsetting some negative effects of warming.

These findings and predictions highlight that peatland is a complex system that does not show a simple linear response to changing climate conditions and there is considerable uncertainty over the current and future state of peatland carbon balance. The main focus of this thesis is to determine whether these climate-sensitive ecosystems will remain a persistent carbon sink or their sequestration capacity will decline over the next 50-100 years making them a carbon source. To understand these convoluted issues, a predictive modelling approach is required that involves all the major key processes and mechanisms of the peatland carbon cycle. Though many peat growth models treat peatlands to varying degrees of complexity (see Table 1), the majority of them lack mechanistic representations of both multi-layer peatland and permafrost dynamics. Similarly, spatial heterogeneity may also be critically important in peatland development but this has unfortunately been ignored in many peatland modelling studies. The process-based dynamic multi-layer approach has been shown to capture reasonable peatland dynamics at the site scale (Bauer, 2004; Frolking et al., 2010; Heinemeyer et al., 2010), but to my knowledge, such a scheme has not been adopted in the framework of dynamic global vegetation models (DGVMs) (see section 1.4) and also has not been applied in permafrost conditions. It is, therefore, essential to include these major detailed components in the present DGVMs to broaden the understanding of the internal processes and mechanisms of these complex systems. Once evaluated, these models can be used over large areas for assessing peat dynamics and regional carbon balance. The LPJ-GUESS DGVM provides a suitable platform to incorporate these important components in its framework and to study the long-term dynamics of peat formation and aggradation based on vegetation litter inputs and decomposition processes.

In this thesis, the implementation of new multi-layer peatland and permafrost dynamics in LPJ-GUESS, a dynamic global vegetation model (DGVM) is described. The vegetation and peatland carbon dynamics are simulated on multiple, connected patches to consider the functional and spatial heterogeneity in peatlands. The first paper (Paper I) focuses on the structure, processes understanding and performance of the model in permafrost and non-permafrost conditions and other independent sites spreading across the subarctic to temperate climate. In the next study (Paper II), the model was applied across the pan-Arctic to predict the past, present and future fate of long-term carbon pools in different climatic zones. The model predictions were evaluated against a number of reported long- and short-term carbon accumulation rates at regional and pan-Arctic scales. The third paper (Paper III) highlights the role of small-scale heterogeneity on the total peatland carbon balance and how closely mircrotopography is coupled with small-scale hydrology, peat accumulation and vegetation dynamics. The last study (Paper IV) focuses on model performance and evaluation with respect to other community models in predicting the soil physical processes in the cold climates.

1.1 Northern peatlands, their distribution and formation

Peatlands are transitional ecosystems mostly present in northern latitudes (Fig. 3) (Gorham, 1991) forming one of the biggest carbon reserves of all terrestrial ecosystems (Yu et al., 2010). Organic carbon stored in these ecosystems comprise one third of the global carbon deposits (Bridgham et al., 2006). Based on the present climate space, these ecosystems exist where the average annual temperature is between 2 and 10 °C and the annual precipitation ranges between 200 and 1000 mm (Yu et al., 2009). Moderate net primary productivity (NPP) coupled with depressed decomposition due to anoxic waterlogged conditions lead to sequestration of considerable amounts of carbon over the course of centuries (Clymo, 1991; Thormann and Bayley, 1997; Frolking et al., 2001). Peatlands have accumulated carbon at a rate of around 15–30 g C m^{-2} y^{-1} since the Holocene (Yu et al., 2009; Loisel et al., 2014). Overall, this imbalanced process has accumulated approximately 500±100 PgC across an area covering about 3.5 million km^2 (refer to Fig. 3) (Gorham, 1991; Turunen et al., 2002; Yu, 2012).

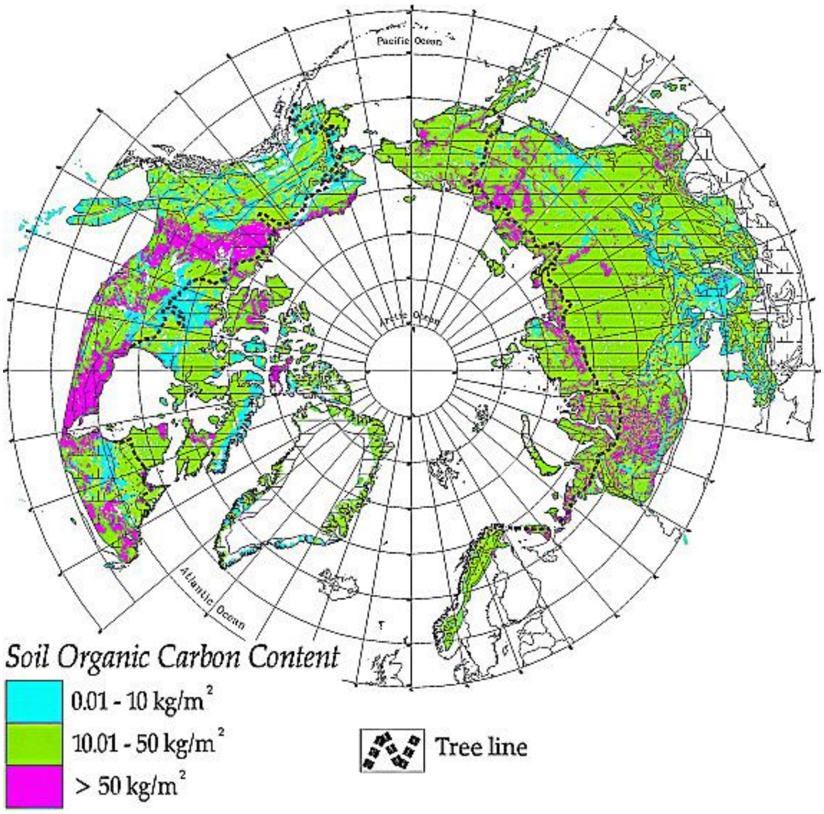

Figure 3 Soil organic carbon distribution in the northern latitude regions. Reproduced from Tarnocai et al. (2009) (Figure 3, page 6) with the kind permission of John Wiley and Sons under license no: 4073780673118

Peatland forms primarily either by paludification on a flat or depressed waterlogged mineral soil surface or on the moist surface that emerged from the ice or sea after deglaciation through isostatic rebound, or by filling up of shallow water bodies known as terristrialisation (Anderson and Foster, 2003; Kuhry and Turunen, 2006; MacDonald et al., 2006). The drainage of glacial lakes exposing the rich mineral soil also promoted these ecosystems (Vitt, 2006; Klein et al., 2013).

New land surface availability due to the retreat of massive ice caps (Dyke et al., 2004; Gorham et al., 2007), associated deglaciation warming (Kaufman et al., 2004), higher summer insolation (Berger and Loutr, 2003) marked by pronounced seasonality (Yu et al., 2009), emissions of greenhouse gases (GHGs) (MacDonald et al., 2006) together with elevated moisture conditions (Wolfe et al., 2000) are some other crucial factors that shaped and promoted the rapid expansion of peatlands in northern latitude regions.

Basal ages are commonly used as proxies to determine the approximate peatland inception period. Extensive basal databases indicate regional differences and a lag with respect to climate warming and ice retreat (MacDonald et al., 2006; Yu et al., 2010; Loisel et al., 2014). According to these datasets, the majority of the northern peatlands developed between ca. 8 and 12 kyr ago (see Fig. 4), after the deglaciation of the pan-Arctic region (MacDonald et al., 2006).

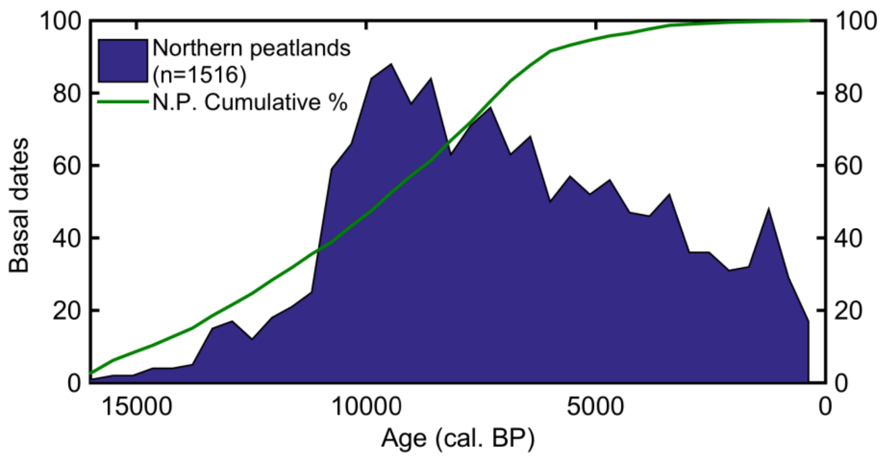

Figure 4 Observed peat basal ages and peat initiation histories plotted as a frequency curve and cumulative percentage (in green) for northern peatlands (used MacDonald et al. (2006) dataset to develop this plot)

1.2 Permafrost

Soils at or below 0 °C for at least two or more consecutive years are considered permafrost soils (Riseborough et al., 2008; Harris et al., 2009). The majority of northern peatlands overlap with low altitude permafrost areas (compare Fig. 3 and Fig. 5) (Tarnocai et al., 2009; Wania et al., 2009a, b; Kleinen et al., 2012). The peat deposits in combination with permafrost lead to assorted land structures such as palsa, peat plateaus and polygonal peat plateaus with shallow ALD (Vardy et al., 2000). The cold and frozen climate conditions prevalent in these regions create an inert environment suppressing the heterotrophic decomposition rate. The presence or absence of underlying permafrost also has diverse effects on peat accumulation and hydrology (Malmer et al., 2005). Having a strong coupling with all major biogeochemical components, any alterations in the present state of permafrost will have severe implications on the overall peatland carbon balance (Robinson and Moore, 2000).

Globally, permafrost peatlands store around 277 PgC which is equivalent to around 14% of the global soil carbon store (Tarnocai et al., 2009). In North America, permafrost peatlands store around 53.5 PgC, while non-permafrost peatlands store around 124.6 PgC with current sequestration rates of 6.6 and 22.6 TgC y^{-1}, respectively (Bridgham et al., 2006) equivalent to 12.9 g C m^{-2} y^{-1} for permafrost and 25.3 g C m^{-2} y^{-1} for non-permafrost peatlands (Wania et al., 2009a). This indicates how the frozen conditions in subarctic and arctic settings constrain peat accumulation by affecting aboveground vegetation and hydrology (Vardy et al., 2000). However, the presence of permafrost also promotes peat production by impeding drainage leading to moist and inundated conditions that lead to higher peat accumulation (Robinson and Moore, 2000). In turn, peat deposits and aboveground vegetation also affects permafrost by altering the soil physical properties and soil thermodynamics. Peat soils composed of organic recalcitrant carbon mass have, when dry, a low heat capacity and thermal conductivity which affects the presence and extent of permafrost underneath (Nicolsky et al., 2007).

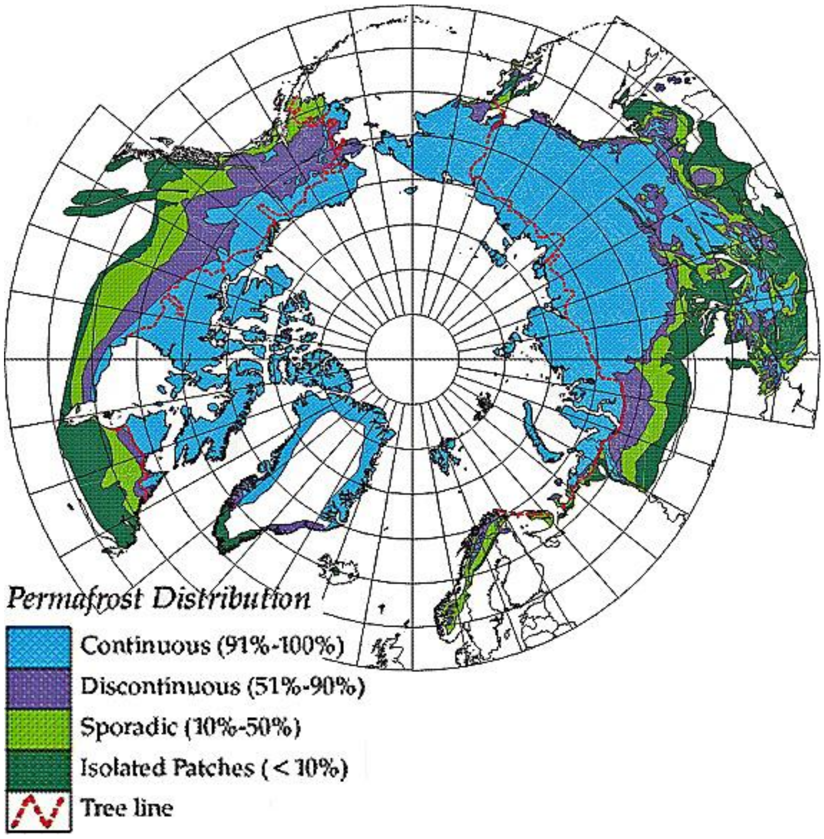

Figure 5 Permafrost distribution in the northern latitude regions. Reproduced from Tarnocai et al. (2009) (Figure 1) with the kind permission of John Wiley and Sons under license no: 4073780673118

1.3 Peatland vegetation and microtopography

The majority of peatlands are characterised by contrasting microstructures at different spatial scales (Weltzin et al., 2001; Belyea and Lancaster, 2002). At the micro scale (1–10 m), hummocks and hollows can be identified (Belyea and Clymo, 1998). Hummocks (see I in Fig. 6) are elevated features in the landscape where the water table is relatively lower than the surrounding sites leading to domination of shrubs and dry *Sphagnum* species (e.g. *S. fuscum* and *S. russowii*). Conversely, the deeper hollow areas (see III in Fig. 6) remain waterlogged and host tall productive and water-resistant species such as graminoids (e.g., *Carex rotundata)* and wet *Sphagnum* species (*S. balticum* and *S. riparium)*. Mosses such as *S. lindbergi* grow in the intermediate areas known as lawns (see II in Fig. 6) and are found between the above two extremes. Open deep-water pools are also common in many peatlands and are often devoid of any vegetation (see IV in Fig. 6).

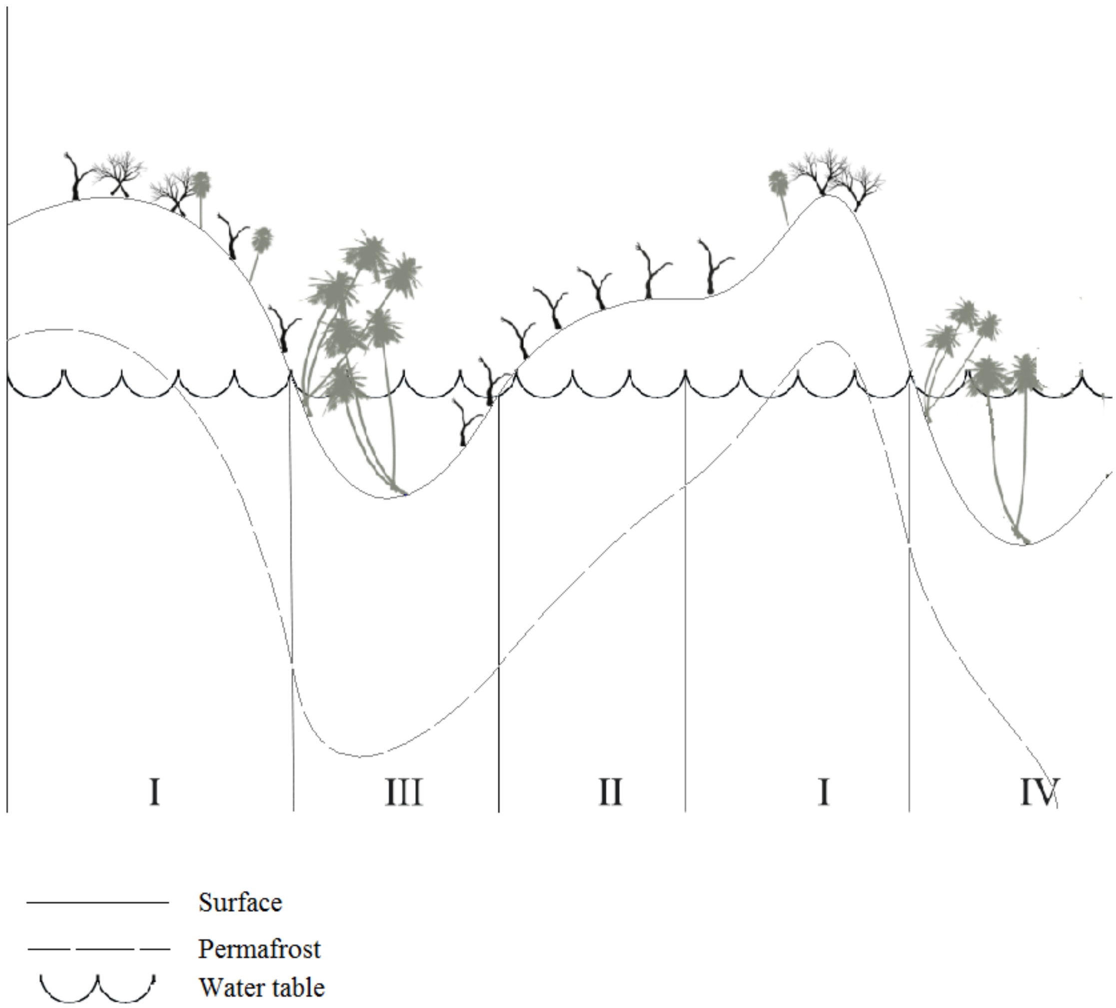

Figure 6 A schematic representation of different site classes found in the peatlands -hummocks (I), lawns (II), hollows (III) and pools (IV) and their permafrost and hydrology regimes. Modified from the source: Johansson et al. (2006).

These microstructures differ with regard to vegetation cover, hydrology, nutrient status, carbon accumulation and decomposition rates (Malmer et al., 2005). The proportion of these small-scale microstructures plays an important role in determining the long-term carbon fluxes in many peatlands (Malmer et al., 2005; Johansson et al., 2006). Changes in regional climatic conditions could have a profound impact on these micro-formations, modifying the peatland carbon balance from micro to macro scales (Johansson et al., 2006; Swindles et al., 2015).

1.4 Peatland modelling with a dynamic global vegetation model (DGVM)

Peatlands are transitional zones between upland mineral soils and wetland ecosystems (Clymo, 1991). Lately, effort have been made to incorporate peatland accumulation processes in different models (see Table 1) to understand their role in sequestering carbon and lowering the radiative forcing in the past (Frolking and Roulet, 2007; Wania et al., 2009a; Frolking et al., 2010; Kleinen et al., 2012; Tang et al., 2015b) and to know how these adaptive systems might behave in the present and potential future climatic conditions.

DGVMs are designed to study past, present and future vegetation patterns together with associated biogeochemical cycles and climate feedbacks at regional and global scales (Smith et al., 2001; Friedlingstein et al., 2006; Sitch et al., 2008; Strandberg et al., 2014; Zhang et al., 2014). They provide a suitable framework for the integration of both peatland and permafrost processes and to study their interactive response on high latitude climate. At present, most DGVMs lack both peatland and permafrost functionality (see Table 1) with a few exceptions (Wania et al., 2009a, b; Tang et al., 2015a). The two aforementioned models (Wania et al., 2009a, b; Tang et al., 2015a) however employed a relatively simple representation of peatland dynamics compared to a process-based dynamic multi-layer approach. Some other modelling groups (non-DGVMs) have also included peatland processes at varied degrees of complexity from simple two-layer to multiple-layer peat aggradation and decomposition schemes (Frolking et al., 2010; Morris et al., 2012; Alexandrov et al., 2016; Wu et al., 2016) but most of them lack permafrost. Nevertheless, they preform reasonably at single and multiple sites (Frolking et al., 2010; Wu et al., 2011; Morris et al., 2012) and also over large areas (see Table 1)(Kleinen et al., 2012; Schuldt et al., 2013; Stocker et al., 2014; Alexandrov et al., 2016).

Table 1. Comparison of functionality and scope of a representative set of current peatland models.

Schemes / Models	Peatland	Permafrost	DGVM	Multiple annual peat layers	Spatial heterogeneity	Methane	Coupled to ESM	Single site	Global/Regional application
This thesis	✓	✓	✓	✓	✓	✕ (Possible)	✕ (Possible)	✓	✓
Wu et al. (2016)	✓	✕	✕	✕	✕	✕	✓	✓	✓
Alexandrov et al. (2016)	✓	✕	✕	✕	✕	✕	✕	✕	✓
Tang et al. (2015b)	✓	✓	✓	✕	✕	✓	✕	✓	✓
Stocker et al. (2014)	✓	✕	✓	✕	✕	✕	✕	✕	✓
Morris et al. (2012)	✓	✕	✕	✕	✓	✕	✕	✓	✕
Schuldt et al. (2013)	✓	✕	✓	✕	✕	✓	✓	✓	✓
Kleinen et al. (2012)	✓	✕	✓	✕	✕	✕	✕	✓	✓
Heinemeyer et al. (2010)	✓	✕	✕	✓	✕	✕	✕	✓	✕
Frolking et al. (2010)	✓	✕	✕	✓	✕	✕	✕	✓	✕
Wania et al. (2009a)	✓	✓	✓	✕	✕	✓	✕	✕	✓
Ise et al. (2008)	✓	✕	✕	✕	✕	✕	✕	✓	✕
Bauer (2004)	✓	✕	✕	✓	✕	✕	✕	✓	✕
Hilbert et al. (2000)	✓	✕	✕	✕	✕	✕	✕	✓	✕
Clymo (1984)	✓	✕	✕	✕	✕	✕	✕	✓	✕
Ingram (1982)	✓	✕	✕	✕	✕	✕	✕	✓	✕

2. Aim and Objectives

The aim of this PhD project was to implement peatland and permafrost dynamics in a dynamic global vegetation model (LPJ-GUESS) and to evaluate it at different spatial and temporal scales.

The objectives were:

I. To improve the current understanding of the processes and mechanisms involved in peatland development (Paper I)

II. To assess the potential impact of climate change on the peatland carbon balance across the pan-Arctic and to understand its role in future (Paper II)

III. To understand the role of small-scale heterogeneity on coupled vegetation-hydrology and peat accumulation (Paper III)

IV. To evaluate LPJ-GUESS model performance in cold regions and to compare this performance to that of other land surface models (Paper IV)

3. Description of LPJ-GUESS

The Lund-Potsdam-Jena (LPJ) General Ecosystem Simulator (GUESS) is a generalised, process-based model of vegetation dynamics, plant physiology and the biogeochemistry of terrestrial ecosystems optimised for regional and global applications (Smith et al., 2001; Sitch et al., 2003; Miller and Smith, 2012). It simulates individual- and patch- based dynamics of vegetation structure and composition in changing climate and soil conditions. The model has been evaluated in numerous studies, e.g., Sitch et al. (2003), Gerten et al. (2004), Sitch et al. (2008), Piao et al. (2013) and Ekici et al. (2015) and is shown to simulate reasonable ecosystem dynamics, plant geography, and hydrological, biophysical and biogeochemical processes on regional and global scales. It gives a suitable framework for implementing peatland and permafrost dynamics and to study their long-term evolution and dynamics. Figure 7 outlines the steps involved in developing the two-dimensional microtopographical (2-DMT) and LPJ-GUESS Peatland models in this thesis.

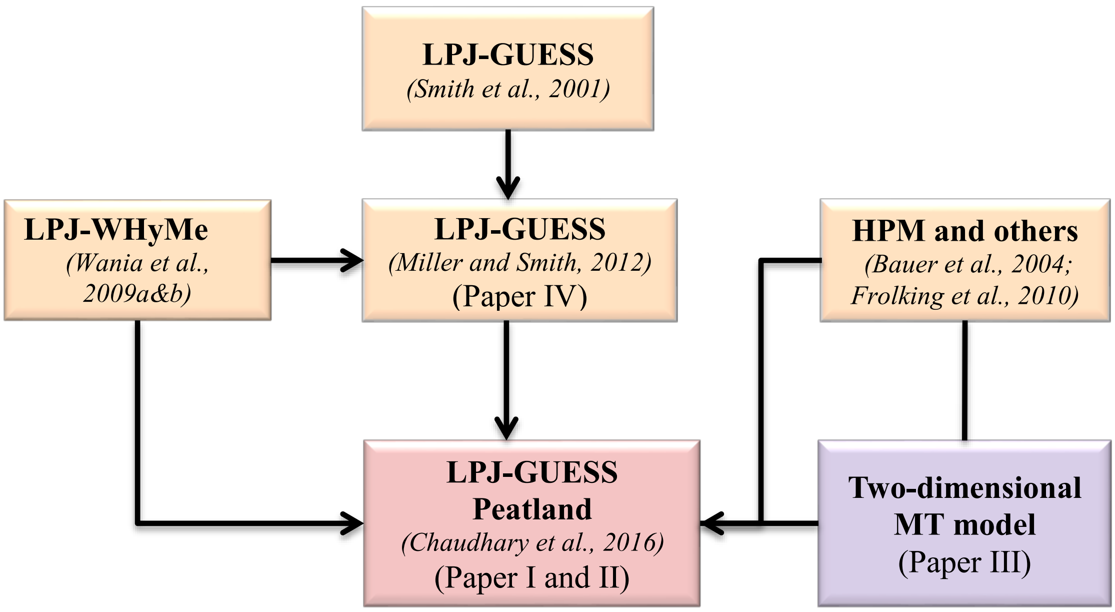

Figure 7 Flowchart depicting the steps involved in developing the two-dimensional microtopographical (2-DMT) and LPJ-GUESS Peatland models for this thesis. The model description can be found in each reference cited therein.

3.1 LPJ-GUESS Peatland

A customised Arctic version of LPJ-GUESS (Smith et al., 2001; Miller and Smith, 2012) is employed in three studies (Papers I-II and IV) in this thesis. It incorporates representations of hydrological, biophysical and biogeochemical processes characteristic of upland and peatland ecosystems of the tundra and taiga biomes (McGuire et al., 2012; Miller and Smith, 2012). I developed the model to include dynamic, multi-layer peat accumulation and permafrost dynamics (Miller and Smith, 2012; Chaudhary et al., 2016) (see Fig. 8). In the present approach, vegetation and peatland carbon dynamics are simulated on multiple, connected patches (approx. 10 ha) across the landscape to consider the functional and spatial heterogeneity of peatlands. The number of patches (total 10) is fixed at the outset of the simulation. In the first year, the model randomly distributes the carbon (after spinup) in each patch over the static mineral soil layers leading to an initially heterogeneous surface (different patch heights). These patches have their own soil column (composed of mineral and, eventually, peat layers) and dynamic vegetation properties. Vegetation in patches competes for water and sunlight and evolves as an outcome of this competition. However, there is no communication between patches except for the distribution of water. Each patch is separated vertically into four distinct layers. On the top is the dynamic single snow layer of variable thickness. Underneath it, litter/multiple peat layers of variable thickness exist. For Stordalen (see section 3), 4739 + 100 peat layers were simulated, i.e., one peat layer for each of the 4739 years after inception until the year 2000, followed by a 100-year projection from 2001 to 2100. Beneath these multiple peat layers there lies a mineral soil column composed of upper (0.5 m) and lower (1.5 m) mineral layers of fixed depth and finally a “padding” column of 48 m depth (with thicker sublayers).

To calculate the soil temperature, the peat column is subdivided into seven sublayers in the case of Stordalen, starting with the three sublayers and adding a new sublayer after every 0.5 m peat depth increment. The mineral soil layers (i.e., below the peat layers) are subdivided into 20 sublayers of 10 cm thickness. These sublayers play an important role in simulating the Arctic soil thermal dynamics at different depths. The soil temperature in the peat column and mineral soil is the result of presence/absence of insulating snow cover, phase change between water and ice, peat thickness, water input from precipitation and snowmelt and surface air temperature.

A traditional water bucket scheme was used to simulate the peatland hydrology where precipitation (rain or snowmelt) is considered the main source of water input. Water-balance processes such as evapotranspiration, drainage, surface, and base runoff determine the amount of water and ice in each layer and eventually determine the water table position (WTP). Peat layers above the WTP are assumed to remain completely unsaturated. In the saturated layers, the amount of water and ice is limited to its water-holding capacity. The water and ice fractions in each peat layer of each individual patch are simulated daily, based on soil temperature in that layer on that particular day.

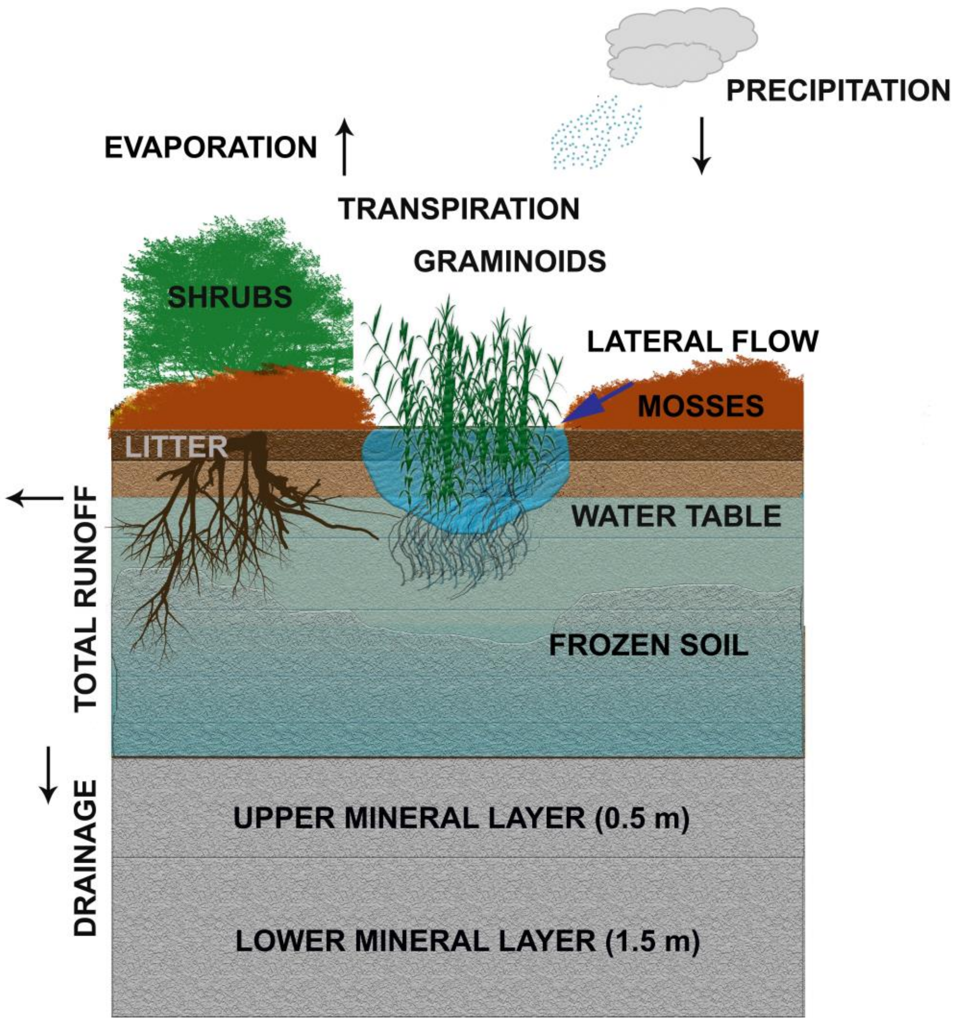

Figure 8 Schematic representation of peatland structure and function described in this thesis (Paper I). Dynamic peat layers accumulate above the static mineral soil layers (0.5+1.5 m). In the shallow peat, plant roots are present in both mineral and peat layers. Once the peat becomes sufficiently thick (2 m), all roots are confined to the peat layers.

The model also includes lateral flow of water between patches that has been missing from many earlier peatland models. Water is redistributed from the higher elevated patches (hummocks) to low depressions (hollows) using a simple lateral flow scheme in which the WTP of individual patches is held at the mean WTP of the landscape. As the peat accumulates, the individual patches develop their own hydrologies and water-holding capacities leading to different water heights in each patch. The mean landscape WTP is calculated by taking the mean of the WTP across all patches at the end of the simulation in daily time step. This in turn affects the plant productivity and decomposition rate in each patch, which further modifies the surface conditions.

Five plant functional types (PFTs)—mosses (M), graminoids (Gr), summergreen and evergreen low shrubs (LSS and LSE) and summergreen high shrubs (HSS)—are considered. Each PFT has its own parameterisation of physiological processes related to photosynthetic pathway, leaf thickness, carbon allocation, plant phenology, and rooting depth (Miller and Smith, 2012). The PFTs establish only within the prescribed bioclimatic conditions and are also constrained by an annual average WTP (aWTP) limit. Shrubs grow in relatively dry conditions when the aWTP is deeper than 25 cm while mosses and graminoids thrive in relatively wet conditions. Mosses establish when the aWTP is between +5 and –50 cm and graminoids grow when the aWTP is above +10 cm. The establishment function is implemented once per annual time step based on the mean WTP of the previous 12 months.

The annual addition of peat layers together with annual average decomposition rate controlled by hydrological and thermal properties in each layer governs peat accumulation. Every year fresh litter is deposited on top of the mineral soil and decomposes for the entire year based on the surface soil temperature and moisture conditions. However, litter formed of plant dead roots is added directly to the peat layers corresponding to the location of the roots. The litter pool is composed of 17 plant parts (roots, seeds, wood and leaves) deposited by different PFTs based on their plant productivity, mortality and leaf turnover properties. These individual components decompose at different rates and this difference in decomposability between litter types is represented by the initial decomposition rate (k_o) (Aerts et al., 1999; Frolking et al., 2001), which declines over time as the peat becomes older.

At the start of the simulation, plants access water from the static upper (0.5 m) and lower (1.5 m) mineral soil layers. However, annually changing peat height necessitated a modified root fraction scheme which determines the amount of daily plant water uptake. In the standard set-up, plant roots fractions are prescribed in upper and lower mineral soil layers. In the modified implementation, the root fractions in the mineral soil layers are reduced linearly as peat accumulates and the corresponding reduction of root fractions is added in the peat layers, enabling PFT individuals to access water from the peat layers. Mosses are assumed to have shallow rooting depth and access water only from the top 50 cm of the peat surface. Other PFTs have deeper rooting depths that decline linearly as peat grows and they continue to access water from both mineral and peat soils. Once the peat height reaches 2 m, they access water only from the peat soil. A detailed description of the model can be found in Paper I.

3.2 Two-dimensional microtopographical model

In Paper III, I developed a simple two-dimensional microtopographical (2-DMT) model to investigate and understand the intricate relation between small-scale heterogeneity and coupled vegetation-hydrological dynamics, and the implications of divergent microtopographical behaviour on peatland carbon balances. The model shares peat accumulation and hydrological characteristics with LPJ-GUESS. Five different plant types have been considered in this study—shrubs, graminoids and three mosses dominant in their respective niches (wet, dry and intermediate peatland areas). The soil temperature in this model is calculated in a much simpler manner by adopting the simple analytical approach used in the LPJ-GUESS (Smith et al., 2001; Sitch et al., 2003), which in turn determines the amount of ice and water in the peat soil. Net primary productivity (NPP) is not simulated in 2-DMT. Rather, NPP is taken as an input to the model (from a separate LPJ-GUESS simulation for the same area), representing landscape-level primary productivity, and the model distributes it among plant types according to their productivity and dominance. The vegetation dynamics is determined by the position of the annual average WTP. The model used a simple lateral flow scheme (see above) that distributes water on the daily time-step across the patches (total 50). Figure 9 shows the schematic representation of 2-DMT and the details on this model can be found in Paper III.

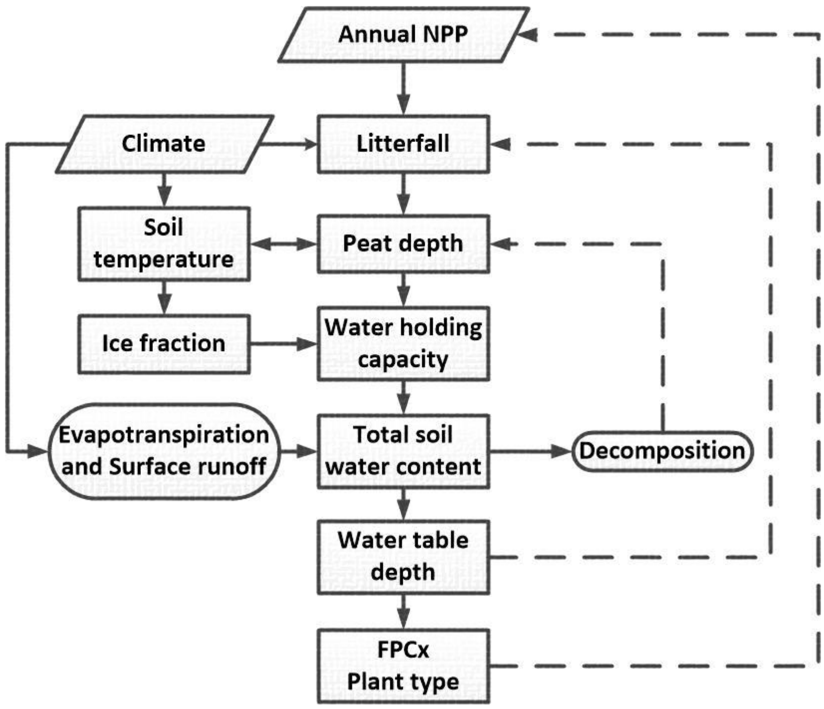

Figure 9 Schematic representation of the two-dimensional peat microtopographical model, 2-DMT. Model inputs are depicted by parallelograms, state variables are in rectangle boxes and processes are present in round boxes.

4. Study area, data and experiments

The LPJ-GUESS and 2-DMT models were tested and calibrated at Stordalen, a subarctic mire situated in the north of Sweden (68.36° N, 19.05° E, elevation 360 m a.s.l.). It is one of the most studied mixed mires in the world and was therefore considered appropriate for developing and evaluating the models (Papers I and III). Additionally, the performance of LPJ-GUESS was evaluated against the measurement and observations at Mer Bleue, a raised temperate peatland in Canada (45.40° N, 75.50° W, elevation 65 m a.s.l.). To further validate the performance of LPJ-GUESS across high-latitude climatic gradients, ten additional simulations were performed at different locations across Scandinavia (see Table 2 and Fig. 10) for which observations of peat depth were available; of these, three sites were evaluated against additional variables such as ecosystem carbon fluxes, WTP, long-term "apparent" rate of carbon accumulation (LARCA) and dominant plant type. These ten sites represent different types of peatlands with distinct initialisation periods from relatively new to old sites and diverse climatic zones from cold temperate to subarctic sites. In Paper II, the model was further applied at 180 randomly selected sites distributed among 10 zones across the pan-Arctic between 45 and 75 °N to assess the effects of historical and projected climate on LARCA at regional scales. Each zone consists of 10–20 random points (see Paper II). The soil thermal dynamics and freezing-thawing properties of the model were tested and evaluated at four distinct cold sites ranging from high-latitude to high-altitude regions (see Paper IV). In Paper I, each simulation was run for 5 to 10 kyr based on the reported peat inception period, while in Paper II, all the points are run for 10 kyr. In Paper III, the model was run only for 1 kyr and in Paper IV, the simulations are done only for the recent climate (1901–2010). In the first two papers (Papers I and II), the simulations comprised three distinct climate forcing periods, the first, Holocene phase, lasted 5–10 kyr BP until 0 BP, assumed to be the year 1900. The second, historical phase ran from 1901 until the year 2000. Finally, the future scenario phase ran from the year 2001 until 2100. The detailed processing of Holocene climate forcing data was explained in Paper I. In Paper III, historical (last 1 kyr) and transient (1901–2000) runs were performed while only transient run (1901–2010) was carried out in Paper IV. Table 2 summarises the location and time periods for evaluating the model performance in this thesis, the validation datasets used and the model climate forcing data.

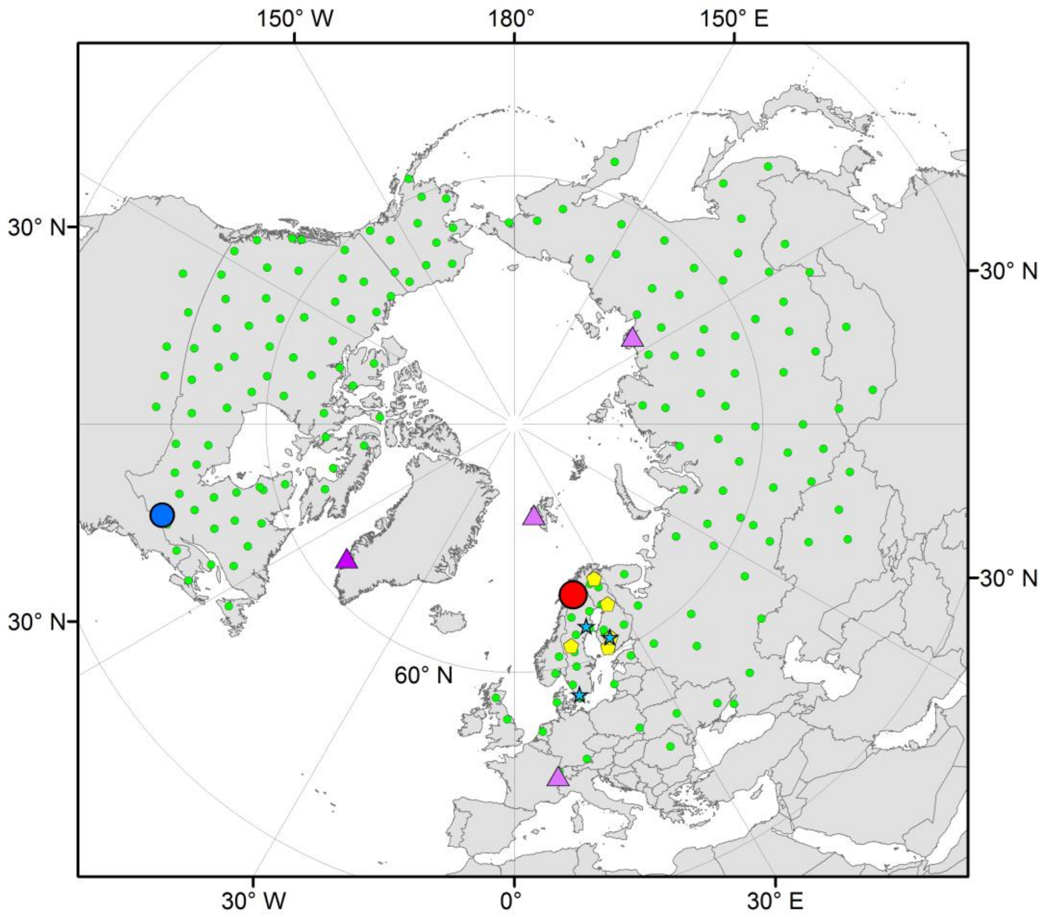

Figure 10 Map showing the selected study sites and randomly selected points used in this thesis (for symbols see Table 2).

Table 2. A summary of the simulations and model experiments described in this thesis: location, time periods for evaluating the model performance, validation datasets and climate forcing data used

Paper	Study site	Purpose of the simulation	Location(s)	Climate forcing data	Evaluation data	Period	Symbol in maps and Figure 10
I & III	Stordalen	Calibration & Evaluation	Scandinavia	Holocene climate anomalies[1] + average observed climate (1913–1942) – Observed climate[2] (1914–2000) – RCP8.5 and RCP2.6[3] (2001–2100)	Peat depth[4], LARCA[4], NEE[5], WTP[6], ALD[6] Vegetation dynamics[4], Porosity[4] & Bulk density[4]	4.7 (1.0)[7] kyr cal. BP-2100	
I	Mer Bleue	Evaluation	Canada	Holocene climate anomalies + average CRU climate (1901–1930) – CRU[8] climate (1901–2000) – RCP8.5[3] (2001–2100)	Peat depth[9] & LARCA[9]	8.4kyr cal. BP -2100	
I	3 sites	Evaluation	Scandinavia		Peat depth[10], LARCA[10], NEE[10], WTP[10] & dominant PFT[10]	5 to 10kyr cal. BP-2100	
I	5 sites	Evaluation	Scandinavia		Peat depth[11]	5 to 10kyr cal. BP-2100	
II	180 sites	Application & Evaluation	pan-Arctic		pan-Arctic[12] & regional LARCA[13]	10kyr cal. BP-2100	
IV	4 sites	Evaluation	Eurasia	WATCH[14] data (1901-2010)	Soil thermal properties & permafrost[15]	1901-2010	

1 Miller and Smith, 2012
2 Yang et al., 2012
3 Moss et al., 2010 and http://tntcat.iiasa.ac.at/RcpDb/; page visited 18th March 2017.
4 Kokfelt et al., 2010, Malmer et al., 2005 and Ryden et al., 1980
5 Deng et al., 2014 and Tang et al., 2015a
6 Tang et al., 2015a, b
7 Model was run for the last 1kyr in Paper III
8 Mitchell and Jones, 2005
9 Frolking et al., 2010 and Wang et al., 2014
10 Lund et al., 2007, Sagerfors et al., 2008 and Aurela et al., 2007
11 Makila et al., 2001, Aurela et al., 2004, Tuittila et al., 2007, Valiranta et al., 2007 and Andersson and Schoning, 2010
12 Yu et al., 2010 and Loisel et al., 2014
13 See Table 2 in Paper II
14 http://www.eu-watch.org/data_availability; page visited 18th March 2017
15 Ekici et al., 2015

5. Results and discussion

5.1 Implementing the current knowledge and progression in understanding of peatland development using LPJ-GUESS (Paper I)

Processes such as dynamic annual peat accumulation (Frolking et al., 2010), freezing-thawing (in subarctic and arctic conditions) (Wania et al., 2009a) and lateral flow (Belyea and Baird, 2006) are essential in the peatland modelling. Much of the understanding of these processes in peatland functioning is available in published literature (Yu et al., 2009; Frolking et al., 2010; Baird et al., 2013a; Baird et al., 2013b; Belyea, 2013; Frolking et al., 2013). My work builds upon the existing knowledge of these processes involved in long-term peat accumulation and its internal dynamics, including how these systems are influenced by small-scale heterogeneity, vegetation dynamics and underlying permafrost. My syntheses (see Table 1) showed that the current models (DGVMs and others) have not yet considered all aforementioned processes in their framework. Though many DGVMs (see Table 1) have simplified peat accumulation schemes, the majority of them lack permafrost as well as representations of small-scale heterogeneity questioning their applicability in areas where they occur. Hence, their inclusion in the modelling framework will be beneficial in predicting the past and future peatland dynamics not only at site scale but also in large areas (pan-Arctic). In this study, dynamic multi-layer peatland and permafrost dynamics are included in the Arctic version of LPJ-GUESS. Vegetation and peatland carbon dynamics are simulated on multiple, connected patches to account for the functional and spatial heterogeneity in peatlands (see Fig. 8). I used the resultant model representation to study the emergent patterns, variability and trends in the peatland ecosystems.

The model performed satisfactorily when confronted with experimental data, with modelled estimates such as long-term peat accumulation patterns, vegetation dynamics, carbon fluxes, permafrost, WTP, bulk density and porosity values (see Figs. 11 and 12). However, it was not able to reproduce the right peat accumulation pattern in some regions. This could be because of the unavailability of site-specific climate forcing data, peat inception period or dominant vegetation cover (presence of trees in some regions), an incorrect initial bulk density profile or the model's failure to capture the local hydrological conditions.

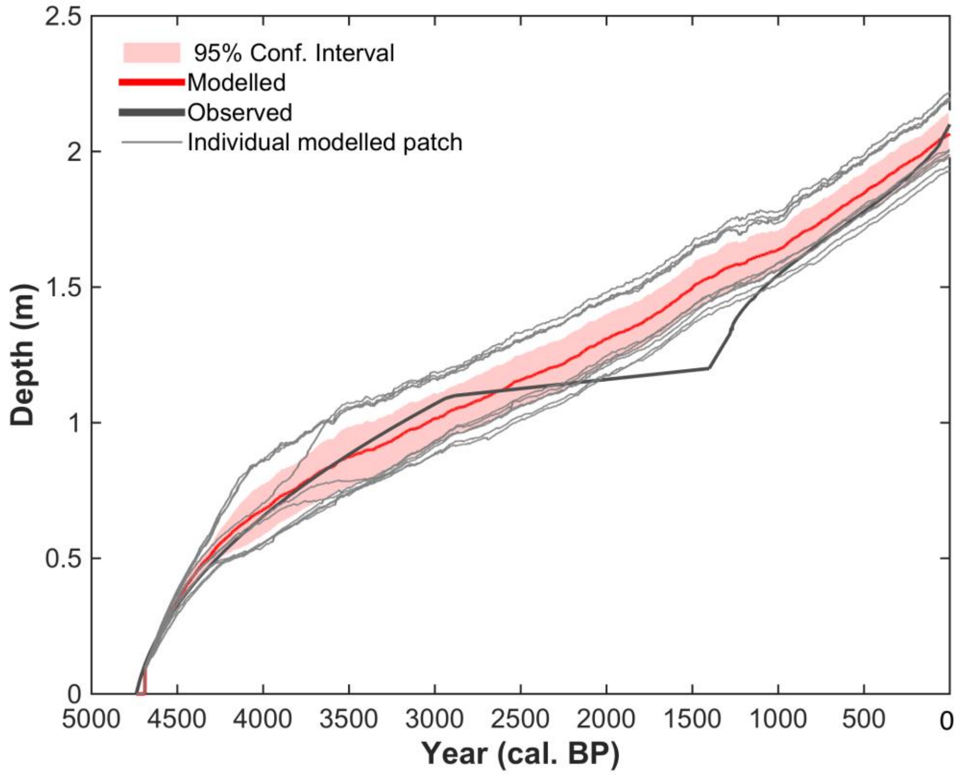

Figure 11 Comparison of mean landscape simulated peat depth (m) with inferred ages of peat layers of different depths in peat cores from the Stordalen mire. The light red shaded area shows the 95% confidence interval (CI) inferred from the variability among simulated patches at each site (shown in light grey lines).

The model simulated reasonable vegetation dynamics in the majority of the evaluation sites. However, in some instances, the dominant pattern was not captured well because plant dynamics is closely linked to the variability in local climate conditions. These biases and errors in climate data are likely to be higher in palaeoclimate simulations due to the absence of instrumental observations for validating the models. There could be additional bias also due to the interpolation procedure used during the conversion of global climate model (GCM) results into monthly anomalies. For instance, in Stordalen, between 700 and 1700 cal. BP graminoids were the dominant peat-forming vegetation but the model could not reproduce this phase due to the absence of decadal and centennial climate variability in the adopted climate-forcing data. This has resulted in an averaging out of high-moisture periods over time removing some wet episodes essential for graminoids to be sufficiently competitive (Fig. 12a).

The model has simulated reasonable ALD in hummocks and semi-wet patches (see Fig. 12b) with similar temporal pattern indicating that it is quite effective in capturing permafrost dynamics. The magnitude, variability and trend of the simulated annual ALD were close to the observed values. The simulated annual ALD was shallow in drier elevated areas while deeper in wet hollows, a phenomenon observed in many permafrost peatlands (Johansson et al., 2013). Simulations also demonstrated that how the permafrost affects the productivity of vascular plants and the overall ecosystem. For instance, vascular plants have a deeper rooting depth and their access to water decreases significantly if the peat soil is frozen. This reduces their net productivity and in turn affects the total litter biomass. This condition marginally affects the mosses as they access water only from the top 50 cm of the soil. This is also a reason why mosses are the dominant PFT in majority of the subarctic settings.

Simulation results show that the bulk density does not increase with depth in the colder regions. Some studies also indicated the bulk density to be highly variable down the profile (Tomlinson, 2005; Baird et al., 2016). This is because the lower peat layers were frozen, didn't decompose significantly and their bulk densities remain lower relative to other partially frozen or unfrozen layers.

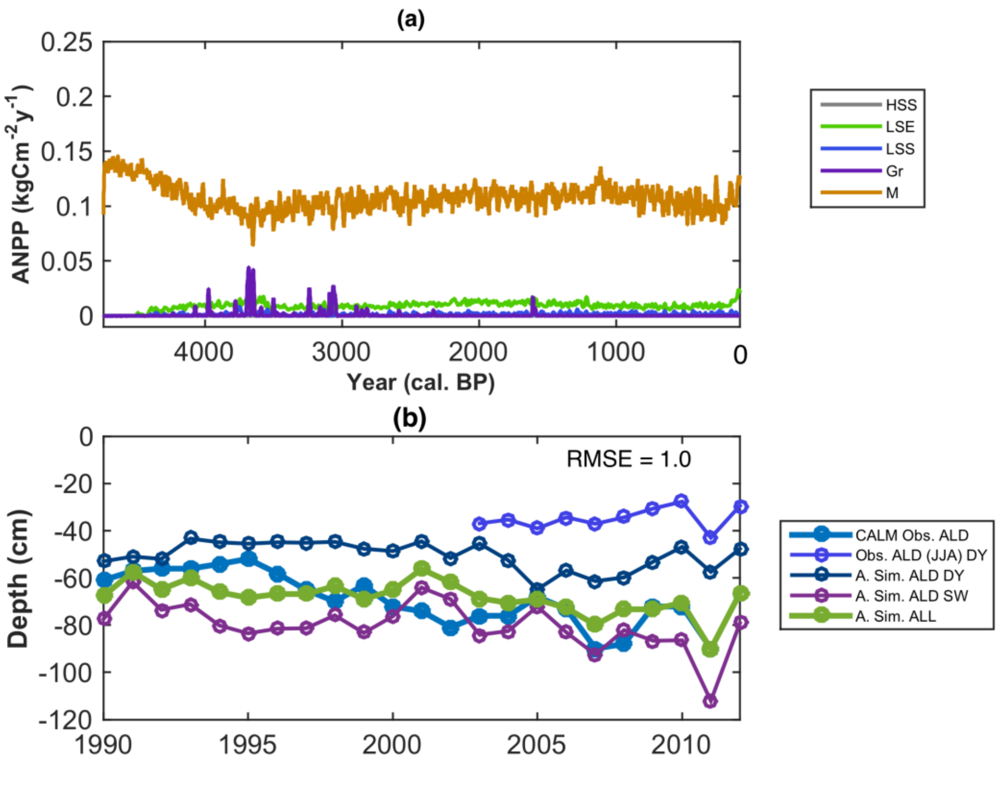

Figure 12 (a) Simulated annual net primary productivity (ANPP in kg C m^{-2} y^{-1}; 10-year moving average) of simulated PFTs. **(b)** Comparison between annual observed (CALM Obs.) and simulated (A. Sim. ALL) active layer depth (in cm) for 1990-2012 and annual average simulated ALD in semi-wet (A. Sim. SW) and dry patches (A. Sim. DY) at Stordalen mire. A separate short mean (June-August) ALD observation from the Stordalen in a dry elevated hummock site (Obs. ALD (JJA) DY) is also presented.

The above discussion shows that LPJ-GUESS is quite robust in capturing peat accumulation and permafrost dynamics including reasonable vegetation and hydrological conditions (see Fig. 8 in Paper I). The simulations also demonstrate that how these processes are intricately linked and help us in better understanding of the peatland functioning. The model also predicts the vulnerability of Stordalen mire to climate change and the results indicate that the mire may sequester more carbon until the middle of this century due to the prevailing mild climate conditions and then turn into a carbon source due to higher decomposition rate as a result of warming of soils and in more extreme case the permafrost might completely disappear.

These findings suggest that the model is capable of capturing the reasonable patterns, trends and variability associated with Stordalen mire and also reproduced satisfactory results at other sites (see Paper I); hence, it can be used to predict the past, present and future trends in carbon accumulation making a basis for my second study (Paper II). With incorporation of the aforementioned processes, LPJ-GUESS has now become quite robust and can be coupled with ESM to resolve the issues related to peatland-mediated biogeochemical and biophysical feedbacks to climate change in the Arctic as well as globally.

5.2 Predicting the past, present and future carbon accumulation rates across pan-Arctic (Paper II)

Many empirical studies have reported and compiled carbon accumulation rates across the pan-Arctic (Yu et al., 2009 and Table 3 in Paper II) and the recent syntheses by Loisel et al. (2014) highlighted certain gaps in some key regions such as eastern Siberia, Far East and European Russia due to the remoteness, inaccessibility and harsh climate conditions. My process-based peatland and permafrost modelling complements the empirical knowledge and fills the existing gaps related to carbon accumulation rates at different spatial and temporal scales and demonstrates the potential implications of current warming on these ecosystems. In this thesis (Paper II), LPJ-GUESS was employed at 180 randomly selected points distributed among 10 zones across the pan-Arctic (45–75 °N) to determine the carbon accumulation rates and to examine the implications of the projected climate change on peatland carbon dynamics.

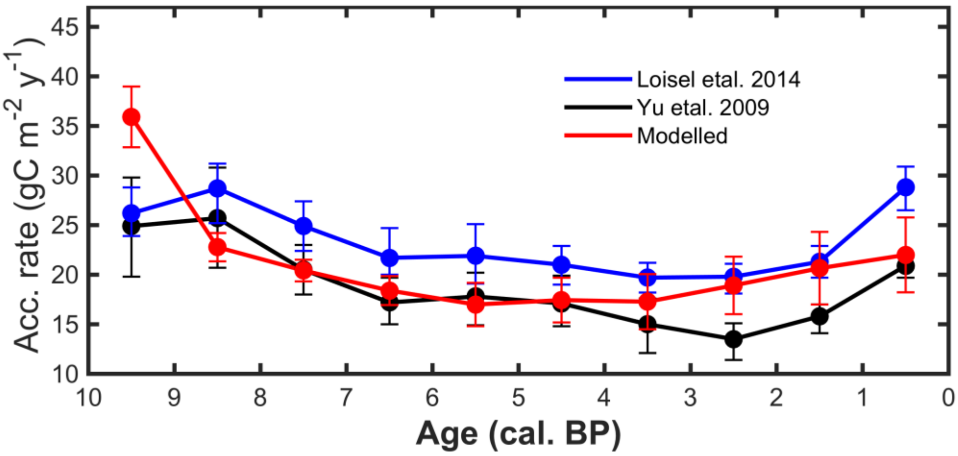

Figure 13 Simulated and observed mean carbon accumulation rate (g C m^{-2} y^{-1}) for each 1 kyr period for the last 10 kyr. Red: simulated mean (and standard error of the means) carbon accumulation rates based on 180 random sites. Blue and black points observed carbon accumulation rates (g C m^{-2} y^{-1}) based on 127 (Loisel et al., 2014) (blue points) and 33 sites (Yu et al., 2009) (black points) across northern peatlands with error bars showing standard errors of the means.

My result shows that the mean modelled LARCA (20.8 ± 12.3 g C m^{-2} y^{-1}) across the pan-Arctic falls within the reported range (18.6-22.9 g C m^{-2} y^{-1}) for the northern peatlands (see Fig. 13) (Yu et al., 2009; Loisel et al., 2014). The reported value obtained from Loisel et al. (2014) is more comprehensive (n = 127) than that of Yu et al. (2009), which contains only 33 sites, and with limited or no sites from many important peat-rich regions such as the Hudson Bay Lowlands, the British Isles, western and eastern Siberia. However, the Loisel et al. (2014) dataset is not completely representative of the pan-Arctic region either (see above). This dataset includes points mainly from peat rich complexes, whereas shallow peat basins are underrepresented (MacDonald et al., 2006; Gorham et al., 2007; Korhola et al., 2010). Furthermore, their dataset was limited to area north of 69 °N. Inclusion of shallow peatland complexes and more arctic sites in their syntheses might conceivably bring down the mean observed LARCA value closer to the modelled LARCA. However, the temporal pattern and overall trend of the modelled, regionally-averaged carbon accumulation rates (n = 180) for the last 10 kyr agrees reasonably closely with the published syntheses (Fig. 14a) and is also consistent with many reported regional estimates (see Paper II, Table 3).

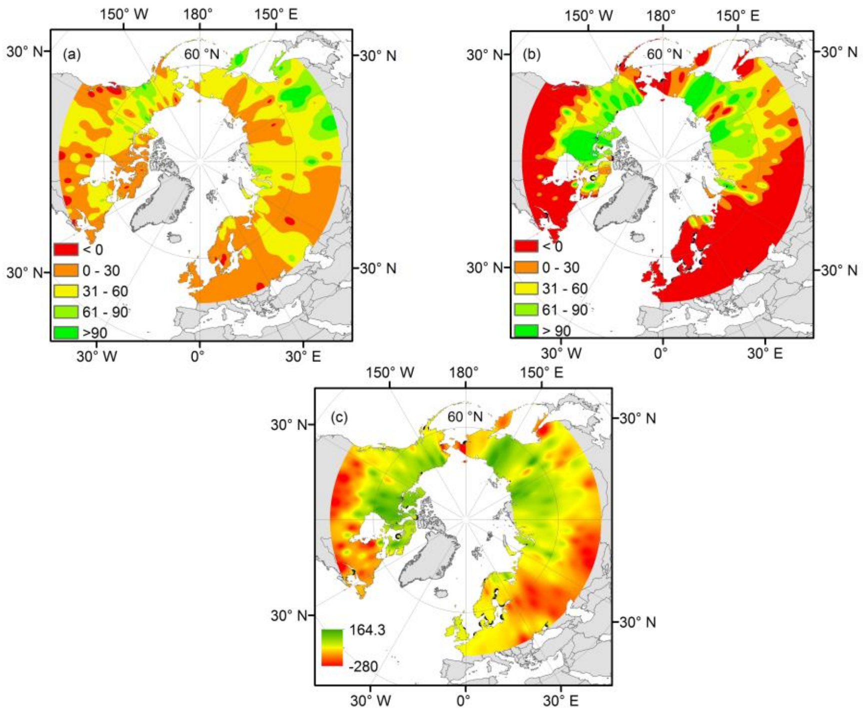

Figure 14 Modelled mean carbon accumulation rate (g C m^{-2} y^{-1}) interpolated among simulation points for (a) 1990-2000, (b) 2090-2100; (c) Net change in total accumulation rate (b-a).

The results show that the carbon sequestration capacity of major peat-rich regions such as Siberia, Far East Russia, Alaska and western and northern Canada would be enhanced by 2100. In contrast, regions such as Scandinavia, Europe, Russia and central and eastern Canada may turn into carbon sources (Fig. 14b,c). This indicates a shift in the carbon balance of major peat-rich regions. However, the projected readjustment affects the pan-Arctic carbon accumulation rate marginally and is predicted to decrease from 20.8 g C m^{-2} y^{-1} to 20.78 g C m^{-2} y^{-1} under extreme (RCP8.5) climatic conditions. Simulation results also highlighted that permafrost-free regions predicted to experience reduced rates of precipitation may lose significant amount of carbon in the future due to reduction in soil moisture; in contrast, peatlands currently underlain with permafrost could gain carbon in the coming decades due to an initial increase in soil moisture as a result of permafrost thawing (see Fig. 5 in Paper II).

5.3 Modelling the coupled dynamics of vegetation-hydrology and peat accumulation (Paper III)

Scaling is an important issue in peatland science because the majority of peatlands are marked with small-scale microstructures known as hummocks and hollows (see Fig. 6) (Weltzin et al., 2001; Belyea and Lancaster, 2002) and this small-scale heterogeneity has a strong influence on peatland carbon balance and regulates carbon fluxes at micro to macro scales (Malmer et al., 2005). The issues related to representation of such heterogeneity and their generalisation in GCMs are often discussed but not implemented due to sheer complexity and resource availability. In Paper III a simple 2-DMT model was developed to address the hypotheses concerning the stability, behaviour and transformation of these microstructures and the effects of the small-scale heterogeneity on coupled dynamic of vegetation-hydrology and peat accumulation. The main focus of this study is on understanding the processes operating at or near the peatland surface as well as across the peat column and how they are closely linked to and impact the overall peatland carbon balance.

I found a very interesting result which shows that peatlands can exhibit cyclical pattern in some patches (see Fig. 15). Shrubs and hummock mosses in some elevated areas (patches) replaced each other and the transition period lasted 50–150 years (Fig. 15a). During the transition, both the plant types coexisted. High rate of litter deposition by hummock mosses led to domination of shrubs as the WTP drew down from the surface. However, relatively high decomposition rate of shrub litter reduced the growth rate of peat column and soon the WTP approached the surface leading to favourable conditions for the hummock mosses to flourish. Similar cyclicity was also observed between lawn and hummock mosses but for a shorter duration (Fig. 15b). These dynamics may be crucial for the evolution of large-scale peatland carbon balance under changing climate conditions. However, it is likely challenging to emulate with accuracy due to the strong influence of internal feedbacks suggested by my simulation results (see Fig. 5 in Paper III).

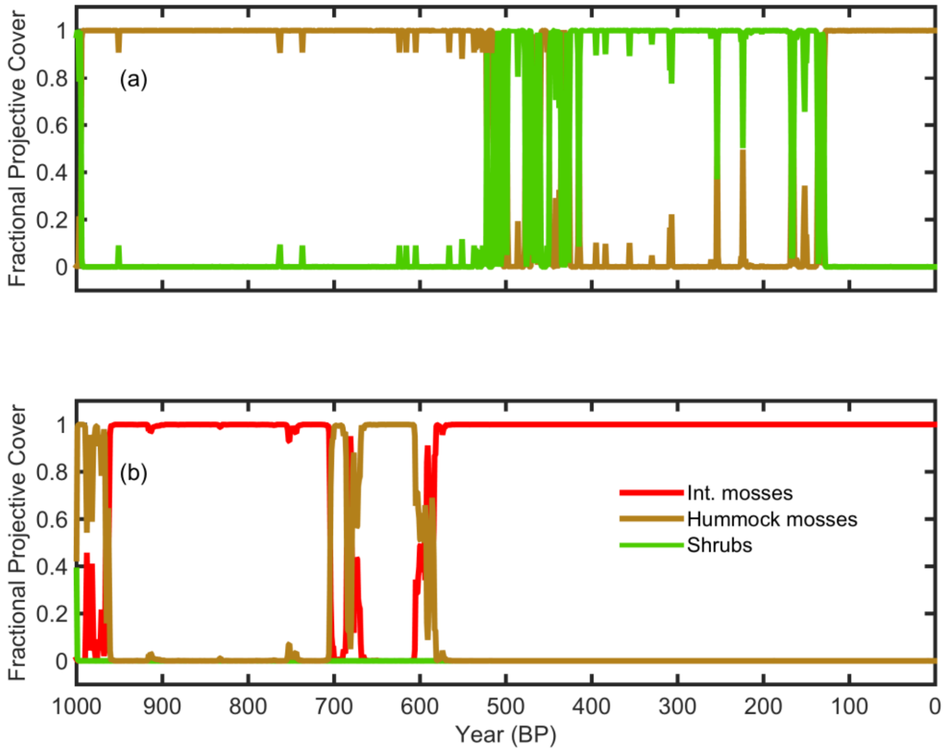

Figure. 15 (a) Cyclicity between shrubs and hummock mosses is apparent from ca. 600 cal. BP and (b) in intermediate and hummock mosses from ca. 950 cal. BP

Generally, the results indicate that peatland can show diverse ranges of behaviour with alternative compositional and structural dynamics depending on the initial topographical and climatic conditions, and plant characteristics. Some patches showed a cyclical behaviour while other remain stable over the course of the simulation but overall the peatland loses its initial surface roughness. Hence, this varied transformational behaviour of microstructures poses certain challenges to the representation of such dynamics in ESMs, allowing their potentially important implications for regional and global carbon balances and biogeochemical and biophysical feedbacks to the atmosphere to be explored and quantified.

5.4 Modelling soil thermal dynamics in high latitudes and high altitudes–a model intercomparison study (Paper IV)

Defining soil physical properties such as snow insulation, soil freezing and thawing and sub-surface conditions like water/ice content and soil texture are crucial for modelling the right soil thermal dynamics at high-latitudes and high-altitudes. Paper IV in this thesis presents a comparison of six different land surface models to identify the importance of physical processes in capturing observed temperature dynamics in soils. The model comparison is carried out at four different sites distributed from Alpine to high Arctic and wet polygonal tundra to non-permafrost Arctic. The study emphasised that the inclusion of detailed snow dynamics in the land surface models is important as the variation in the snow depth affects the topsoil temperature and its inclusion may further enhance the model predictive power. In the snow-free season, dynamic vegetation cover and organic/litter layer influence the topsoil temperature predictions and considering such dynamics is essential. On the other hand, dynamic heat-transfer parameters (volumetric heat capacity and heat conductivity) in snow representation appear less important because of the missing processes such as wind drift. We found some discrepancies in modelling subsoil temperature between the land surface models. These discrepancies in predicting the subsoil temperature stem from different hydrological and thermal dynamics in model formulations and the analysis indicates that the right subsoil temperature can be captured using a detailed soil-physics scheme. LPJ-GUESS modelled reasonable topsoil (see Fig. 16) and subsoil temperatures but its predictions can be improved further by including multi-snow layer scheme and detailed representation of dynamic organic surface layer and hydrology. In the subsequent study (Paper I), some of these issues were addressed and a dynamic multi-layer peatland and hydrology were incorporated in the model.

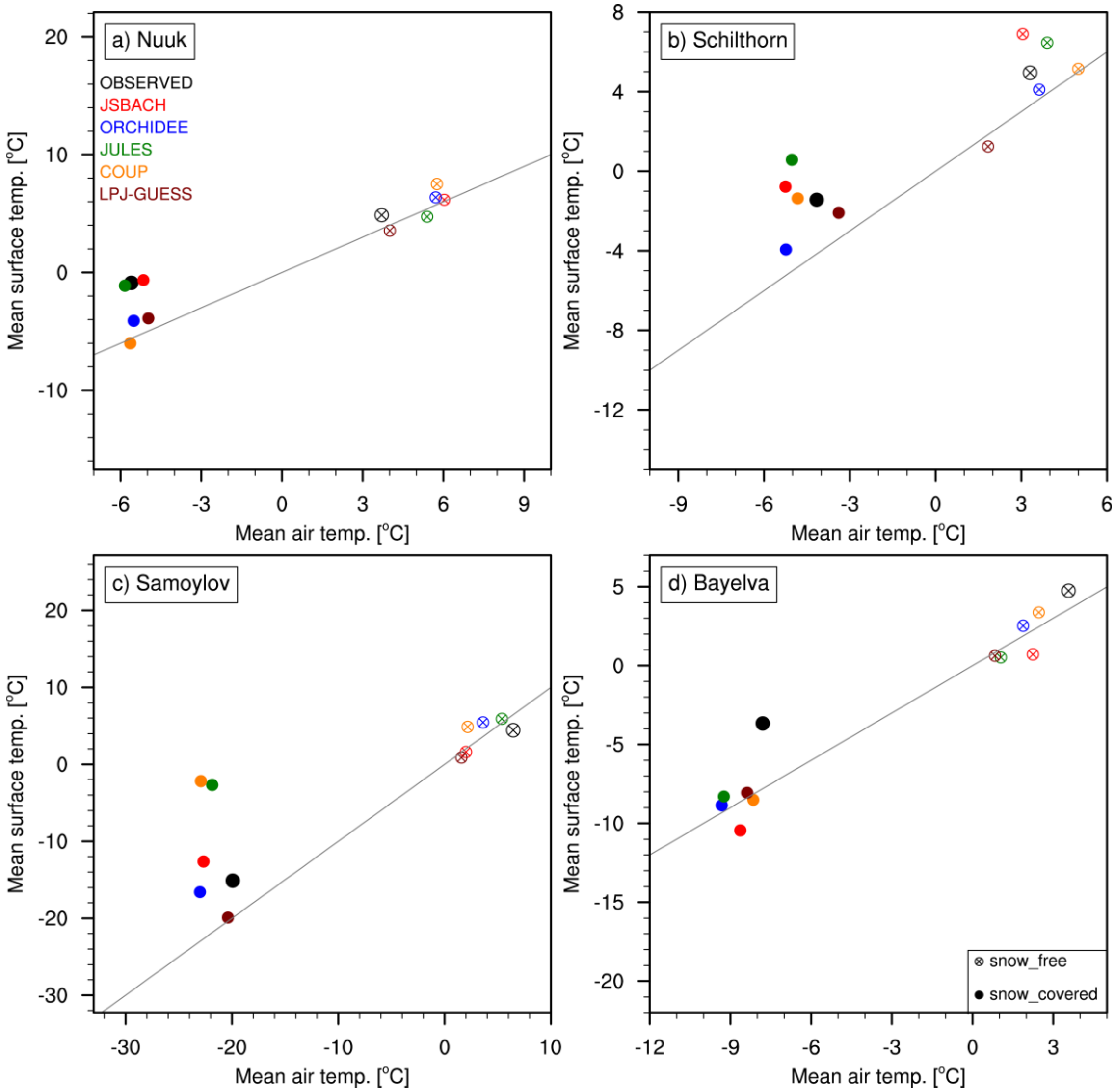

Figure 16 Scatter plots showing air/topsoil temperature relation from observations and models at each site for snow and snow-free seasons. Snow season is defined separately for observations and each model, by taking snow depth values over 5 cm to represent the snow-covered period. The average temperature of all snow covered (or snow free) days of the simulation period is used in the plots. Markers distinguish snow and snow free seasons and colors distinguish models. Gray lines represent the 1:1 line.

5.5 Future development and applications

In this thesis, the advantages of LPJ-GUESS peatland have been highlighted and the model has been shown to capture reasonable peat and permafrost dynamics. The model can further be improved or extended incorporating the following features:

- Peatland is a major source of methane, one of the potent GHG (Lai, 2009). Methane emissions are controlled by some crucial factors such as anaerobic biogeochemistry, soil moisture, plant types and quality of litter (Whiting and Chanton, 1993). Similarly, transport of dissolved organic carbon (DOC) in peatlands is also critical for their carbon balance. Multiyear observations show that export of DOC is between 10 and 20 g C m^{-2} y^{-1} and it has the same order of magnitude as LARCA in many peatlands (Roulet et al., 2007; Nilsson et al., 2008). In LPJ-GUESS, both these components exist in different versions that can be incorporated in the multi-layer peat scheme to simulate more realistic carbon budget and GHG flux estimations.

- Soil moisture above the WTP is essential for moss growth, CH_4 emissions, decomposition and plant productivity (Clymo, 1991). However, currently, the model (this version) uses a simple water bucket scheme and peat layers above the WTP are assumed to be completely unsaturated. The existing hydrology scheme can be further improved to strengthen the current predictive power of the model and associated mechanisms.

- Trees are one of the essential dominant PFTs in many peatlands and their inclusion can further benefit the model simulations in tree-dominated bogs (Lund et al., 2007). However, currently, there are issues in dealing with carbon produced by the trees. Dead litter components such as woody debris and trunks leave a huge mass of carbon affecting the peat layers, distorting the hydrology schemes. Further research is required to deal with this issue.

- Paper IV highlights the importance of including dynamic snow scheme in capturing the topsoil temperature. The model predictions can further be improved by including the multi-layer snow scheme in the cold regions (Ekici et al., 2015).

- Palsa formation and collapse are quite common in subarctic and arctic conditions (Swindles et al., 2015). They influence the peat formation rate and small-scale heterogeneity. The model can further be strengthened if the process related to palsa formation such as ice expansion and compression are added. This will help in capturing the events related to palsa development and collapse. The thawing of ground can lead to soil subsidence (Johansson et al., 2006), a phenomena which is being noticed in many degraded palsa mires such as Stordalen. Inclusion of soil expansion and compression scheme can help in capturing these processes.

- Wind plays an important role in ecosystem functioning but surprisingly has not been considered in majority of the studies and its inclusion will strengthen the simulations (Malmer et al., 2005). For instance, exposure to wind may contribute to reduce plant productivity, abrasion of palsa site, snowdrift and degradation of hummocks sites. Therefore, considering wind and associated factors may certainly reduce some uncertainty.

- Natural disturbances such as fire play an important role in peatland functioning (van Bellen et al., 2012). Little is known about peatland recovery after fire and how they affect palsa formation as well as how they influence plant demography. Its inclusion (peat combustion) in LPJ-GUESS can help in understanding the role fire played in the past and its consequences on permafrost and vegetation dynamics. Many peatlands are currently under huge pressure due to anthropogenic influence and accounting for them in the modelling framework is challenging but a suitable strategy is needed for its representation.

- Many northern peatlands are currently lacking additional nutrients, especially nitrogen (N) and potassium (K). The role of nutrients in these peatlands need to be evaluated by incorporating them in model nutrient biogeochemistry (Smith et al., 2014). It is necessary to understand how these ecosystems may behave in the future due to nutrient loading. Recently, LPJ-GUESS included plant and soil N dynamics in its framework and the updated model can be synced in with the multi-layer peat scheme to simulate the effects of N on peatland functioning.

- My simple modelling approach showed that the inclusion of different mosses (dominant in their respective niches) can help to understand more detailed processes in peatland functioning such as eco-hydrological feedbacks but the question arises as to whether including additional plants in DGVMs will add any further predictive power to the model. This needs to be tested.

- Many tropical peatlands have different processes and are not known in detail. Their inclusion in LPJ-GUESS can make it more robust and can be used to carry out global simulations to simulate the global carbon accumulation rates and to quantify CH_4 budget (Yu et al., 2010; Kurnianto et al., 2015).

- Crout et al. (2009) showed that a well-established and popular wetland CH_4 model is over-complicated and can achieve the same predictive success in much simpler form. Models are often more complicated than they need to be. Based on this observation, the 2-DMT can further be improved by including dynamic vegetation cover constrained by climate conditions, soil expansion and compression schemes.

The improved model can be used to conduct a comparative study of the parsimonious approach and DGVM models.

- The extensive peat inception database (≈ 1500 basal age points; MacDonald et al., 2006) indicates regional differences in the timing of peat initiation. Other such datasets also exist (Gorham et al., 2007; Korhola et al., 2010) and can be combined. The collated dataset can then be interpolated and utilised for prescribing the model (see Fig. A1 in appendix). This interpolated dataset removes the uncertainty related to different timings of peat initiation as a result of the remnants of ice sheets or some other local factors.

- A knowledge of the underlying topography (below the peat deposit) is required for modelling the peat initiation periods but no such dataset exists. However, the current topography can be utilised for this purpose and can be combined with TOPMODEL approach to identify the timing of peat initiation. The simulated results can be compared with the observed datasets (see Fig. A1).

- Currently, static wetland maps are used to prescribe the model simulation in large areas (Wania et al., 2009a). Using the TOPMODEL approach (Kleinen et al., 2012; Stocker et al., 2014), the dynamic inundated area can be calculated which can further be utilised to delineate the past, present and future peatland distribution; it may also be used to predict the likely peat inception periods.

- In some peatlands, bulk density increases with depth due to compaction (Clymo, 1991) but other studies show no net increase (Tomlinson, 2005; Baird et al., 2016). My results indicate that the bulk density doesn't increase with depth in the subarctic conditions and is quite variable. It is an interesting finding and can be tested at other sites in different climate gradients to understand how it varies down the peat profile.

- The role of natural pipes is important in distributing water, solutes, dissolved gases and sediments (Smart et al., 2013). Very little is known about these natural pipes and its implications on peatland functioning. Further research is required how to include such processes in peatland models.

- The peatland stores huge amount of carbon and is not known how they influence the current rate of warming through biophysical and biogeochemical feedbacks (Frolking et al., 2013). LPJ-GUESS can be coupled with the recent ESMs to account for the potentially important (and hypothesised) role of peatlands in the climate system.

6. Conclusions

The main objectives of this thesis were to improve the current understanding of the peatland processes and mechanisms by implementing a detailed peatland and permafrost dynamics in LPJ-GUESS and to assess the implications of changing climate drivers on these sensitive carbon storehouses across the pan-Arctic. I demonstrated that a novel mechanistic multi-layer peat accumulation and decomposition scheme performed fairly well at site and regional scales and model findings are consistent with a broad range of observations.

The main findings of this thesis are:

- LPJ-GUESS is quite robust and can capture the vegetation, physical and hydrological dynamics essential for simulating peatland dynamics at local and regional scales.

- LPJ-GUESS can predict reasonable long-term carbon accumulation rates and the permafrost distribution across the pan-Arctic. My findings may reduce some of the uncertainties related to future peatland and permafrost distributions.

- The results show that climate change can cause many regions to become a carbon source while other regions may enhance their sink capacity across the pan-Arctic, but overall the pan-Arctic sink capacity will remain largely unchanged (similar to 2000) by the end of the century (2100), even under the high-end scenario (RCP8.5).

- The permafrost distribution will drastically reduce and will be limited to central and eastern parts of Siberia and the north Canadian region by the late 21st century, disappearing from large parts of western Siberia and southern parts of Canada, and with very little presence in Scandinavia.

- The small-scale spatial heterogeneity is an important component in many peatlands and to generalize them in large-scale land surface schemes is challenging.

- LPJ-GUESS has captured reasonably the soil thermal dynamics in distinct cold regions and could be further improved by adding a physical multi-layer snow scheme.

In future, I plan to incorporate CH_4 biogeochemistry and nutrient dynamics and the updated model will be used to assess the implications of projected climate change and atmospheric CO_2 on peatland vegetation and GHG exchange across the pan-Arctic. Another plan is to couple the LPJ-GUESS with the atmospheric component of a regional ESM to examine the role of peatland-mediated biogeochemical and biophysical feedbacks to climate change in the Arctic and globally.

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Some thoughts…

When I was a kid I always used to think what exists beyond my house, my locality…

Then I found there is a vast space outside my imagination…

A lot of people with so many different qualities….

Later, I found I am a part of a community, a state and a country…

Then, I realized I am a part of a global community…

After that, I realized that we are special living beings in a unique planet that only hosts life in this Solar system….

Stars bigger than our Sun also exist came to my knowledge later …

After that, I realized there are multiple stars, galaxies in the universe…

Beyond that our knowledge is limited…

We don't know what exists beyond that….

What is the shape, size and extent of the universe ….

That always makes me crazy… because beyond that we don't know what exists …

Then, one day I felt we may be a part of a simulation operating at different scales (dimensions)…

I find myself a random variable in my own space but may be I am a constant or a parameter depending upon which perspective you look in. …

And, this randomness can be controlled or directed with right guidance of other stable variables (my supervisors) or random variables (my friends) which we often find in nature

Or all of us are random- helping or destroying each other in this evolution process…

Appendix

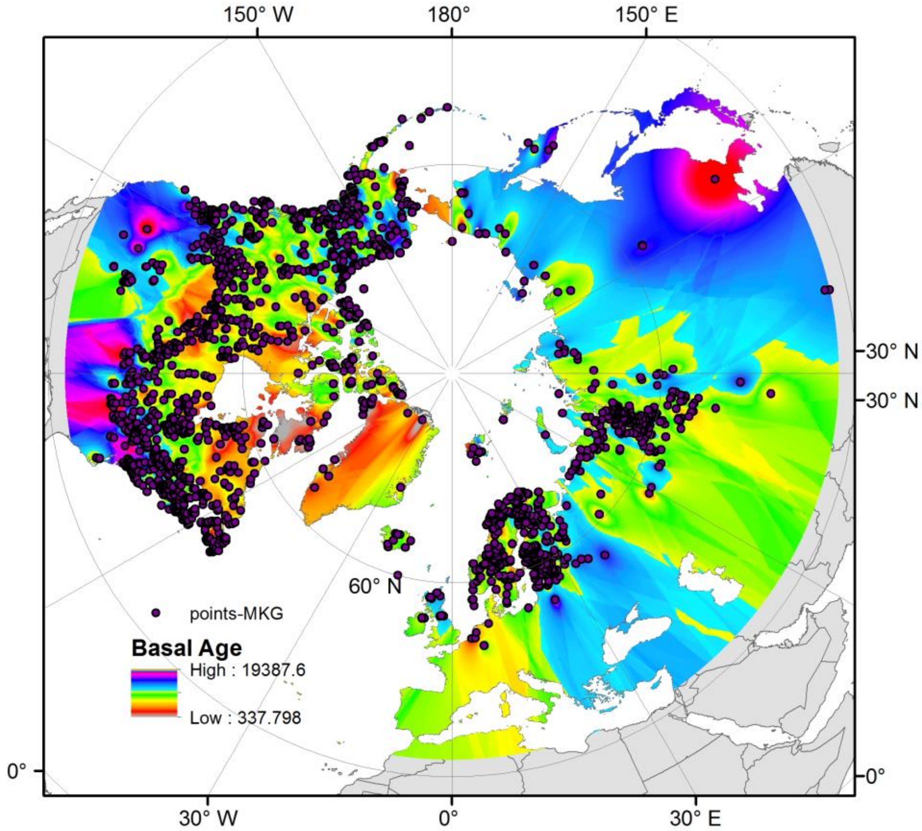

Figure A1 A map developed by interpolating > 2500 observed peat inception points. The dataset is prepared by combining peat inception points of MacDonald et al. (2006), Gorham et al. (2007), Korhola et al. (2010) and other published peat inception observations.

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