A green future with thawing permafrost mires? : a study of climate-vegetation interactions in European subarctic peatlands

Bosiö, Julia

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A green future with thawing permafrost mires?

A study of climate-vegetation interactions in European subarctic peatlands

LUND UNIVERSITY

Julia Bosiö

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

Cover by Julia Bosiö: Photograph of *Eriophorum vaginatum*, Storflaket 2009.

GeoBiosphere Science Center
Department of Physical Geography and Ecosystem Science
Faculty of Science
Lund University
Sölvegatan 12, SE-223 62 Lund, Sweden

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Preface

I began this journey as an undergraduate student, on a road trip through Sápmi, the very northernmost parts of Norway, Sweden and Finland, and the cultural region of the Sámi people. My mission was to capture the southern limits of lowland permafrost. As the rental car silently cruised through the undulating landscape, stunning in its vastness and desolation and perfectly accompanied by the music of Aarctica (a more suitable band for a road trip through the Arctic does not exist), I had the feeling that I was witnessing the extinction of a rare life form. This land of the Sámi people is facing drastic changes according to climate projections, and by the end of this century the particular permafrost formations (palsas) I was hunting may only be found in the archives…

List of papers

I. Future vegetation changes in thawing subarctic mires and implications for greenhouse gas exchange – a regional assessment. *Climatic Change,* 2012 (115)2: 379-398

II. Increased photosynthesis compensates for shorter growing season – seven years of snow manipulation experiments. *Submitted* (Global Change Biology).

Authors contributions

I. The author is lead author and carries the overall responsibility of the paper. The author is also responsible for planning and collection of field data, modeling and analysis.

II. The author is lead author and carries the overall responsibility of the paper. The author is also responsible for planning and collection of field data, and data analysis.

Sammanfattning

Projektioner om framtida klimat i Arktis och subarktis tyder på att drastiska förändrinar väntar regionen under det närmaste århundradet. Inte bara temperaturen spås öka utan även nederbörd, och då framförallt nederbörden under vinterhalvåret. Dessa förändringar kommer sannolikt att ha stor inverkan på miljön i Arktis och subarktis, och stora forksningsansträngningar har redan lagts på att undersöka hur klimat och ekosystem påverkar varandra. Trots detta finns fortfarande luckor i vår kunskap om hur miljön kan tänkas reagera på framtidens klimatförändringar.

I denna licenciatavhandling presenteras min forskning kring kopplingarna mellan klimat och vegetation i permafrostmyrar (även så kallade palsmyrar) in den subarktiska delen av Fennoskandia. Permafrost kallas mark som förblir frusen året om under två eller flera på varandra följande år. I Fennoskandien utgör dessa palsmyrar den yttre gränsen för förekomsten av permafrost i låglandsterräng. En kombination av klimat och miljö gör att marken här aldrig tillåts tina, men förekomsten av permafrost är därmed också mycket känslig för förändingar i klimat och/eller miljön.

Genom att kombinera fältstudier av vegetationsmönster i ett antal palsmyrar i regionen med spatial klimatdata för norra Fennoskandien kunde en projektion av framtida utbredning och förekomst av palsmyrar och dess vegetationsmönster modelleras. Därtill gjordes en experimentell studie i hur ökad snömängd påverkar fotosyntesen i vegetationen på en palsmyr i norra Sverige. Under sju vintrar ökades snömängden med hjälp av snöstaket, varpå effekten på vegetation och fotosyntes undersöktes under två somrar.

Resultaten indikerar att palsmyrar in norra Fennoskandien har små möjligheter att fortsätta existera i ett framtida klimat, där majoriteten av regionens palsmyrar riskerar att tina inom de närmaste 50-60 åren. Även växtligheten beräknas förändras, från torr hedvegetation till fuktig gräsvegetation när dessa palsmyrar tinar och klimat förändras. Experimentella studier av snöns inverkan på vegetation tyder även på att en relativt liten ökning i snömängd kan bidra till en markant förändring i artsammansättning och fotosyntes, till följd av ökad markfuktihet, marktemperatur och näringstillgång. Denna föränding kan bidra till både ökat kolupptag genom ökad fotosyntes, och ökade metanutsläpp då markfuktigehen ökar.

Abstract

Climate projections indicate that Arctic and sub-Arctic regions are facing a significant change in climate during the 21st century. With warmer temperatures precipitation is also expected to increase, and in particular winter precipitation. These changes are likely to have large impacts on the Arctic and subarctic environment, and extensive research has focused on ecosystem-climate interactions in Arctic and sub-Arctic environments, but still the environmental response to such changes is not fully understood.

This thesis presents the work and outcomes of my research on climate-vegetation interactions in permafrost (ground that remains frozen for two or more consecutive years) mires in subarctic Fennoscandia. In this region permafrost mires demarks the outer border of lowland permafrost existence, where a combination of climatological and environmental conditions allows for the ground to remain frozen year round, making the permafrost particularly sensitive to changes.

By combining field observations of vegetation patterns in permafrost mires throughout the study region with spatial data of the present (2008) and projected future climate in subarctic Fennoscandia the future vegetational patterns of these permafrost mires were modeled. Further, the impact of increased snow cover on plant photosynthesis in these environments was assessed through field experiments on a subarctic permafrost mire, where the snow cover was manipulated during seven winters using snow fences.

The results suggest that a rapid transition from dry heath tundra vegetation to moist tussock tundra vegetation is to be expected in these permafrost mires with the warmer climate and increased precipitation projected for the studied region. The snow manipulation experiments suggest that even a moderate increase in snow cover thickness increases plant photosynthesis on the long term. This increase in photosynthesis is attributed to the observed shift in plant species composition where moist tussock vegetation is likely to be favored by increased soil moisture, soil temperature and nutrient availability. However, the increased carbon uptake through higher photosynthesis rates is may be completely offset by increased methane emissions from increased wetness in the thawing peatlands.

Table of Contents

Introduction

The Arctic is facing drastic changes. The people who have been living in the Arctic for centuries have during the last decade been witnessing how a warming climate affects their daily lives and livelihood (Callaghan *et al.* 2011d). However the scientific community, policymakers and media were all taken by surprise by the record low extent of Arctic summer sea ice in September 2012 (Simmonds and Rudeva 2012). Even climate projections could not foresee the rapid melt of Arctic sea ice in the summer that year. This stresses the fact that Arctic ecosystems is strongly linked to both the regional and global climate through feedback mechanisms such as the snow-albedo effect (snow covered areas reflects incoming radiation in contrast to open water that absorbs incoming radiation). It also emphasizes the vulnerability of the environment at high latitude ecosystems with limited possibilities of migration or adaptation. Changes may occur faster than we expect and the environmental impacts of a changing climate are still not fully understood. The overall effect on the long term depends on many factors, including air and soil temperature, changes in hydrological and phenological patterns, nutrient availability, competition between existing and invading species, animal grazing, and human activity. The scientific community is working intensively to better understand the processes linking climate and environment in order to be able to know the prospects of the Arctic under future climate conditions, and new gaps of knowledge continues to appear.

The Arctic and the Fennoscandian subarctic

Geographically the Arctic can be defined as the area north of the Arctic Circle (66° 33'N). Climatologically the Arctic can be defined by the high latitude region where only 2-4 months have a mean temperature above freezing, and where mean temperature of the warmest month of the year is below 10°C, an isotherm that correlates relatively well with the treeline (Smithson *et al.* 2002). The growing season

is short, 2-4 months, and regulated by temperature and light availability. Due to the cold climate the absolute air humidity and precipitation is generally low, and soil water remains frozen during most of the year. Arctic vegetation is therefore often moisture limited. In addition, when soil temperatures are close to 0°C microbial decomposition is slow and the nutrient availability is another limiting factor for plant growth. Under these harsh conditions life has adapted to the cold and dry climate. The vegetation is dominated by grassland, heaths, shrubs and low-growing woody plant species, characteristic for Arctic tundra ecosystems.

In spite of the Gulf Stream bringing warm ocean currents from the tropics and the relatively (at latitudes around 69°N) mild and maritime climate northern Fennoscandia (northernmost parts of Norway, Sweden and Finland) hosts many similarities with the high Arctic, and is often referred to as part of the sub-Arctic. The region (Figure 1) is characterized by the Scandes mountain range that in climatological terms forms a sharp distinction between the coast of Norway and the inland of Sweden and Finland. The mountain range blocks westerly winds from the North Atlantic Ocean saturated with water vapor. The north coast of Norway receives ~1200 mm precipitation annually, while Abisko, a Swedish village located by the mountain foot less than 60 km east of Narvik, a city on the Norwegian coast, receives only ~300 mm annually. This rain shadow effect has a large influence on the regional climate east of the mountain range and affects both vegetation and animal life. The Abisko National Park, located south of the lake Torneträsk, is a popular area for hikers during summer, partly because of the relatively low risk of rain. East of the mountain range the landscape is dominated by heaths and mountain birch forest, featured by rivers, lakes and mires. The long term mean (1961-1990) annual air temperatures range between −4 °C and +2 °C (derived from Hijmans *et al.* (2006)), and the growing season length is approximately 100-120 days (slightly longer in lowland forested areas) within the studied region (Johansen et al, personal communication). The lowest mean temperatures and shortest growing seasons are associated with mountainous areas and the more continental climate of northwest Finland and central parts of Finnmark (Norway).

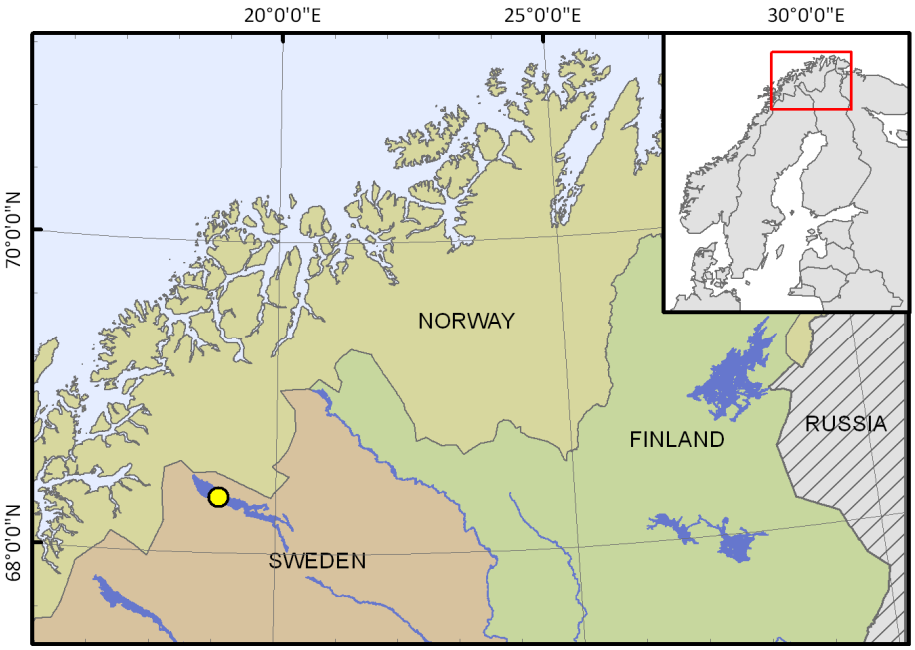

Figure 1. Overview of subarctic Fennoscandia, the focus region of this work. The yellow dot indicates the location of Abisko and Storflaket mire.

Observed and projected changes in climate

Snow is what characterizes the Arctic environment in many ways, and governs microbial, plant, animal as well as human lives. Climate record from various stations around the region show a trend of increasing temperatures and winter precipitation during the 20th century (Callaghan *et al.* 2011a). Since the 1960's climatological changes such as increase in winter temperatures, decrease in snow covered area and snow cover duration have been observed over the Arctic although precipitation patterns in the Arctic are highly variable and not spatially uniform over the region (Solomon *et al.* 2007; Callaghan *et al.* 2011a). In Scandinavia and Eurasia snow water equivalent (SWE) have increased, while North America has experienced a decrease during the 20th century (Kohler *et al.* 2006; Callaghan *et al.* 2011a). In Abisko, located in subarctic Sweden, mean annual temperatures have increased by 2.5°C since 1913 and 1.5°C since 1974 (until year of 2006), and has now crossed the 0°C threshold of mean annual temperature (Callaghan *et al.* 2010).

General circulation models (GCM) project that the Arctic will experience a warming of 3-6°C during the 21st century, twice as high as the global average (Christensen *et al.* 2007; Overland *et al.* 2011). The warming is expected to be less pronounced during summer and more pronounced during fall and winter. With warmer air masses precipitation is also expected to increase, as evaporation and movement of air masses is enhanced by increasing air and surface water temperatures. Although model projections of precipitation, and snow in particular, over the Arctic have shown limitations, both quantitative and qualitative with a large degree of variance between models there remains a strong correlation between increase in air temperature and increase in precipitation. The strongest precipitation increase is therefore projected to occur during winter months (Christensen *et al.* 2007). The assessment report on Snow, Water, Ice and Permafrost in the Arctic from 2011, coordinated by the Arctic Monitoring and Assessment Program (AMAP) conclude that although there are large differences between Arctic regions both the duration of snow cover and the snow water equivalent is projected to decrease over much of the Arctic by 2080. There are however uncertainties regarding changes in snow water equivalent for the first half of the 21st century: the local climatological variations and precipitation patterns makes the projection of snow duration and snow cover a complex task with high uncertainty (Callaghan *et al.* 2011a; Callaghan *et al.* 2011b).

Permafrost in Fennoscandia

In Fennoscandia permafrost (ground that remains at or below 0°C for two or more consecutive years) occurs sporadically, determined by a combination of physical and biological parameters such as altitude, hydrology, snow and vegetation cover and soil type (Johansson *et al.* 2006; Shur and Jorgenson 2007). Lowland permafrost are found in so called palsa mires, or permafrost mires, where characteristic permafrost feature such as palsas or peat plateaus have been formed under a combination of favorable climate conditions and a preserving environment. (Åhman 1977; Seppälä 1986; Zuidhoff 2003). Palsas are peat hummocks with a permanently frozen core, formed in peatlands where the freezing of ice crystals cause an upheaval effect on the peat. These permafrost features require mean annual temperatures below 0°C and low annual precipitation (<400 mm yr^{-1}) (Seppälä 1986; Zuidhoff 2003). The raised hummocks have a generally dry peat layer with low thermal conductivity that

insulates the ground and protect it from thawing during summer. However, with high summer precipitation the heat conductivity of the peat increases and threatens to cause the frozen core to thaw. In winter, a too thick snow cover insulates the ground and prevents it from refreezing after summer thaw (Seppälä 1986, 1994). Individual palsas in Fennoscandia may grow to the size of 3-4 meters in height and several meters across. Palsas may form palsa complex mires, where individual palsas are merged to form a network of ridges and pools, or large, flat peat plateaus. The vegetation in these permafrost mires is tundra-like and varies from dry heath vegetation with lichens and dwarf shrubs to moist or wet tussock vegetation with tall shrubs.

Current knowledge on interactions between climate change, permafrost, and vegetation

During the last decades scientists have presented strong indications that the arctic tundra is warming, and in some cases thawing, at various locations around the northern hemisphere (Romanovsky *et al.* 2010; Callaghan *et al.* 2011a). Parallel with observations of thawing Arctic tundra there are observations of increased greening, plant growth and changes in plant community (Chapin *et al.* 1995; Serreze *et al.* 2000; Sturm *et al.* 2001; Tape *et al.* 2006; Elmendorf *et al.* 2012a). In Fennoscandia signs of permafrost thawing during the latter part of 20th century have been reported (Zuidhoff and Kolstrup 2000; Luoto *et al.* 2004). In northwestern Sweden active layer thickness (the upper layer that thaws and refreezes each year) has been increasing at an accelerating rate by 0.7-2 cm per year since the 1980's (Åkerman and Johansson 2008). In the same region vegetation changes such as decrease of tall shrubs and expansion of tall graminoid vegetation in thawing permafrost mires has been observed (Malmer *et al.* 2005). This is in contrast to the many observation of expansion of shrubs elsewhere in the Arctic (Sturm *et al.* 2001; Tape *et al.* 2006)

The impact that the changes in temperature and precipitation may have on the ecosystem depends to a large extent on the timing of such changes. Warmer temperatures will push the onset of snowfall later into the autumn and enhance snow melt in spring but also increase the probability of winter warming events. A rapid snow melt in late winter or early spring, during which time temperatures may drop well below 0°C at night, may subject vegetation to the risk of frost damage, which eventually will affect the overall productivity. Large damages on *Empetrum hermaphroditum* have been seen in the area between Narvik (Norway) and Abisko

(Sweden) as a consequence of winter warming events when warm temperatures cause the protecting snow cover to melt off, exposing the vegetation to freezing when temperature drops again (Bokhorst *et al.* 2009). Another effect of thaw-and-refreeze cycles during winter are reindeers and other grazing animals suffering from starvation when formation of an ice crust after rain on snow events hinders the animals from reaching the forage below (Callaghan *et al.* 2011c; Callaghan *et al.* 2011d). On the other hand increased winter precipitation may result in a thicker snow pack and a delay of the growing season start, since it takes longer time to melt the thicker snow cover. In a region where the growing season is already very short, a further shortening results in less time to complete the life cycle of plants.

Numerous manipulation experiments have been conducted aiming to capture and describe the driving mechanisms behind observed changes in plant community and plant productivity. One of the most common manipulation experiments is to study the impact of raised air and/or soil temperature on vegetation. These warming experiments have shown different responses in plant community and productivity, differences that can be attributed to ambient climate, water and nutrient availability, vegetation types, seasonality of the manipulation (winter or summer warming) or the duration of the manipulation experiments (short-term or long-term responses) (Grogan and Chapin III 2000; Hollister *et al.* 2005; Natali *et al.* 2011; Elmendorf *et al.* 2012b; Natali *et al.* 2012). The general trend is that vascular plants increase either in height, abundance or biomass as a response to soil and/or temperature warming, and that winter warming experiments promote plant growth partly due to increased thaw depth in summer and partly due to increased nutrient availability, as warmer soil temperatures during winter allows for microbial activity and plant decomposition to continue for a longer period of the year.

Another frequently applied climate manipulation in arctic ecosystems is to control or alter the snow cover (Wipf and Rixen 2010). The presence of snow (and ice) is a contributing factor in keeping temperatures low through its high albedo, reflecting incoming solar radiation. But the snow cover also offers insulation and protection for plants from frost damage and wind abrasion during winter, as described above. Also, the snow pack serves as valuable water storage during the months when plants are inactive, and being released at snow melt when light availability and warmer temperatures triggers plant growth. In an environment where plants are moisture

limited this storage is valuable source of water. Snow manipulation experiments, involving either addition of snow, prevention of snow accumulation, enhancement of snow melt or mechanical removal of snow have focused on changes in plant species composition, plant productivity and soil processes. Similar to the warming experiments snow manipulation experiments results differ with location, experimental setup and ambient climate and environmental conditions and combinatory effects of both warming and increased snow cover.

Objectives

The scope of this work

Through this work my aim is to contribute to the understanding of climate-vegetation interactions in arctic and subarctic environments. The focus lies on the subarctic region of Fennoscandia, and on climate-vegetation interactions in permafrost mires. This may appear to be a very narrow and specific focus with little application outside the studied region. However, these subarctic permafrost mires demarks the border of permafrost existence, and under the current climate in the region, these mires are at the threshold of their existence. They are therefore very sensitive to changes, which allows for a unique opportunity in observing the response to relatively small changes in climate. Studies of these environments may serve as an indicator for what changes that can be expected in similar environments at higher latitudes.

Abisko Scientific Research Station (68°21'N, 18°49'E) has since its establishment in 1913 been a center for environmental and climatological research and monitoring in the Scandinavian subarctic. Research on climate-permafrost-vegetation interactions in permafrost mires is ongoing and extensive, and covers ecosystem fluxes of carbon and nutrients, species dynamics, changes in permafrost and hydrological patterns to only mention a few areas. The main focus of research on permafrost mires has been located to the Stordalen mire where numerous studies have been conducted. The question is whether Stordalen mire is representative for permafrost mires in the region, and whether the results can be generalized and up-scaled (Paper I).

Since subarctic permafrost mires are especially sensitive to snow cover thickness I have chosen to make a case study with special focus on the snow-vegetation interaction, and in particular to what extent increased snow cover affects plant productivity (Paper II).

The objectives of this work is to

- investigate the vegetational patterns in relation to climate in permafrost mires at a regional level in subarctic Fennoscandia in order to *estimate future vegetational patterns and associated greenhouse gas fluxes under the 21st century* (Paper I)

- study the long-term interactions between snow cover and tundra vegetation in a subarctic permafrost mire, addressing the question of *whether the overall productivity accumulated over the growing season benefits from increased snow cover or not* (Paper II)

Material and Method

Vegetational patterns in relation to climate (paper I)

Field observations

The relationship between climate and vegetational patterns in permafrost mires was investigated through field observations of 15 sites distributed within the northernmost parts of Norway, Sweden and Finland (figure 1). The sites were selected based on previous documented occurrence of palsas, palsa complex mires or peat plateaus. The field observations were done during the course of two weeks in August 2008. The vegetational patterns of the sites visited were assessed following a common scheme based on vegetation pattern classification of permafrost mires from previous research (Malmer *et al.* 2005; Zuidhoff and Kolstrup 2005). The sites were classified into two categories, depending on the dominant vegetation type: dry hummock vegetation site or moist hummock vegetation site. In order to upscale the filed observations, the vegetation classification at the sites visited was then correlated the vegetation classification produced by NORUT from satellite derived land cover data of northern Fennoscandia (Johansen *et al.* 2006). This enabled us to map the distribution of mires with similar vegetation patterns (potential permafrost mires) within the study region.

Modeling

In order to estimate the future distribution of permafrost mires under projected climate change, a relationship between climate and observed vegetational patterns, a climate suitability index (CSI) was modeled. The climate parameters included in the climate-vegetation pattern modeling were mean annual air temperature, continentality, summer precipitation and winter precipitation. Spatial climate data of the four climate parameters covering the region were used to compute the CSI at 1 km^2 resolution for three different time frames (2011-2030, 2041-2060 and 2071-

2090). Mapping the potential distribution of permafrost mire vegetation types under future climate scenarios was done by an overlay between the land cover indicating the distribution of permafrost mires and the CSI data sets for the different timeframes. Areas with mapped permafrost mires, and a CSI value above a certain threshold value (CSI_{dry}) was assumed to be classified as dry hummock vegetation sites, while permafrost mire areas with a CSI below the CSI_{dry} threshold was assumed to be classified as moist hummock vegetation sites.

The impact on the regions carbon fluxes caused by the shift from dry hummock vegetation to moist hummock vegetation was estimated through adopting characteristic flux values of CO_2 and CH_4 for the two vegetation types (Bäckstrand *et al.* 2010; Jackowicz-Korczynski *et al.* 2010).

Plant productivity in snow manipulation experiment (paper II)

In order to test the hypothesis of whether long-term increase in snow cover thickness enhances plant productivity a field study of a snow manipulation experiment was done. The specific relationship between plant productivity and long-term increase in snow cover were indirectly assessed through the measurements of absorbed photosynthetic active radiation (APAR). The Monteith equation (Monteith 1972, 1977) describes a linear relationship between gross primary production (GPP) and APAR:

$$GPP = \varepsilon \cdot APAR \qquad (1)$$

where APAR is the absorbed PAR and ε is the light use efficiency of the plant.

Site description: Storflaket

The APAR measurements were conducted on Storflaket (68°20’51” N, 18°57’55” E, 383 m.a.s.l.), a peat plateau located 6 km east of Abisko. The mire covers approximately 13 ha and is characterized by relatively thin peat layer (50-90 cm) underlain by silty sediments. A wet zone crosses the mire, dividing Storflaket into two parts where each part is dry, but with shallow ground settings that contribute to a

variation in soil moisture. Maximum active layer thickness, measured in September, is approximately 50 cm in the dry, elevated parts. However, in the hollows and wetter parts, the active layer may be thicker than 1 m (Johansson *et al.* Submitted). The plant community, consisting mainly of dwarf shrubs, sedges, mosses and lichens, is nitrogen limited (Persson *et al.* 2004) and ranges from dry heath vegetation in the upraised dryer parts to moist tussock vegetation in the depressions.

Plots treated with increased snow cover during winter (achieved by using snow fences to hinder snow drift and enhance snow accumulation) were compared with control plots with ambient snow conditions. The snow manipulations had been running since 2005 while APAR measurements were implemented in 2010. APAR was measured indirectly as the difference between incoming PAR and reflected PAR, assuming that all PAR that is not reflected is absorbed by vegetation. The reflected PAR was logged by EMS Brno's Minikin QT sensors with integrated loggers from, with one down-facing sensor mounted at each plot. Incoming PAR is measured by one up-facing sensor common for the whole mire. The conventional method for estimating or measuring GPP at small scale is the use of flux chambers connected to a gas analyzer. However, this method has several disadvantages. If not implemented for permanent use it is very labor intensive. In addition it is weather sensitive and the installation of the chamber collars (often metal frames inserted into the ground) is likely to have a negative impact on the vegetation (through damage of roots) within the collars. For the purpose of this study the use of the PAR sensors is to prefer. They require minimal maintenance, records continuously at preferred time intervals - without affecting the vegetation productivity. Since the focus of the study was the relative difference between treatment and control plots and not a quantitative GPP measure this was a more suitable approach. To be able to estimate GPP from APAR measurements, the light use efficiency ε of the different plots was studied during a campaign in the growing season of 2010. APAR measurements then were coupled with flux measurements in order to calculate the linear relationship (ε) between APAR and GPP (eq. 1).

Results and discussion

Climate-vegetational patterns in permafrost mires

The field survey of Fennoscandian permafrost mires revealed that permafrost mires indeed share the same vegetational patterns within the region. This supports our assumption that observations within a smaller geographical area such as Stordalen or Storflaket can be generalized and up-scaled within the studied region. The main differences concerned the structure of the permafrost mire (individual palsas, palsa mire complexes or peat plateaus) and the degradation stage of these permafrost features. The most distinct vegetational pattern observed from the sites visited was that dry hummock vegetation, i.e. vegetation in the upraised parts, dominated by dwarf shrubs, lichens and low-growing sedges (figure 2a), had a much narrower span of the CSI. Permafrost mires dominated by moist hummock vegetation (tall shrubs and graminoids, sometimes with carpet mats and water table above the ground surface, (figure 2b)), was present at all sites, while permafrost mires dominated by dry hummock vegetation occurred only at sites where the CSI was relatively high. This indicates a transition from dry to moist hummock vegetation when temperature and/or precipitation increase. The climate – vegetational relationship also indicated that dry hummock permafrost mires are that the verge of its existence. The spatial modeling of permafrost mire distribution under the future climate projected for the 21st century suggests that over 90% of dry hummock permafrost mires will be transitioned into moist hummock permafrost mires, or former permafrost mires (figure 3), as it is unlikely that lowland permafrost can be sustained if temperature increases by 3-6° C – under such degree of warming most of the studied region will have a mean annual temperature well above 0°C.

The indications thawing tundra is alarming; as the permafrost thaws large amounts of organic carbon, previously stored in frozen soil, may be released to the atmosphere through microbial respiration, in the form of CO_2 and CH_4, both greenhouse gases

that may further amplify the warming. The strength of this positive feedback effect (positive in the sense that it reinforces the already ongoing climate change) depends on how much carbon that is released, in which form it is released (since CH_4 is an over 20 times more potent greenhouse gas than CO_2 on a 100 year's timeframe (Solomon *et al.* 2007)) and at what rate the vegetation can offset this release of greenhouse gases by assimilating carbon through photosynthesis. The projections of the future distribution of dry and moist hummock permafrost mires show that the higher carbon uptake in moist hummock permafrost mires is offset by the increased release of methane in the wetter environment, and an overall positive radiative forcing effect (the additional warming effect the release of greenhouse gases have on the climate).

Figure 2a. Example of dry hummock vegetation on top of a 2 m high palsa, where large cracks have beginning to form in the dry peat layer.

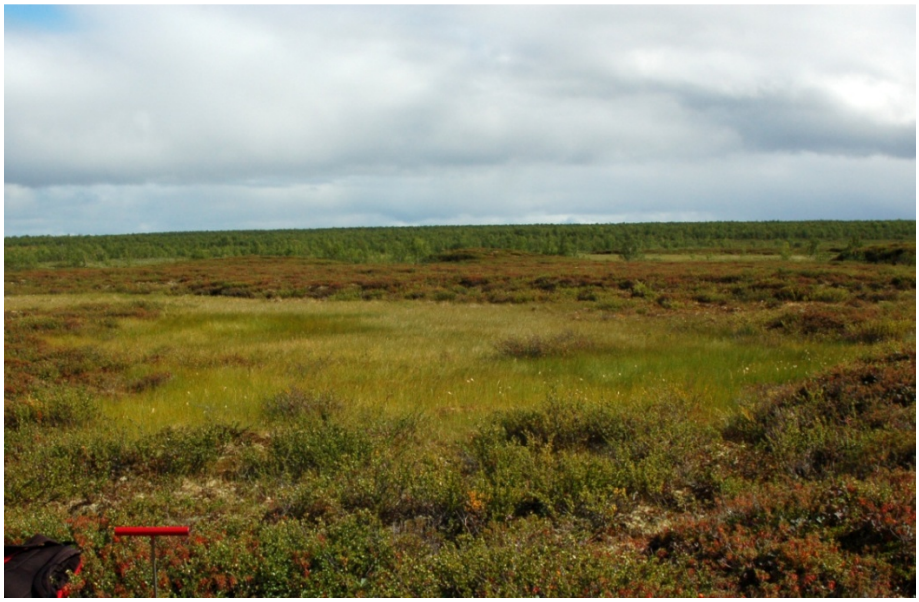

Figure 2b. Example of moist hummock vegetation on a peat plateau. The thawing of permafrost has caused ground subsidence, where the high moisture allows for sedges and tall shrubs to establish.

One of the main uncertainties in the modeled distribution of permafrost mires under future climate scenarios is the low resolution of spatial climate data and lack of information on wind patterns. The 1km^2 spatial of the climate data is too coarse to capture local variability due to factors such as topography, wind exposure, proximity to lake and rivers. These are key parameters in explaining microclimate fluctuations which can be used to model deviations from the average regional climate at local level (Yang 2012). However, such a modeling exercise for downscaling climate projections requires detailed climatological measurements from the area to be studied which to this day is not available except at a few climatological monitoring sites.

No distinction of the impact between the different climate parameters was made, but all four parameters were considered equally important for the vegetational pattern aspect (Paper I). However, Paper II highlights the importance of snow cover duration and it is clear that in a medium-long term time frame winter precipitation as a single factor has a significant impact both on permafrost thawing and active layer thickening, as well as on plant community structure and photosynthesis.

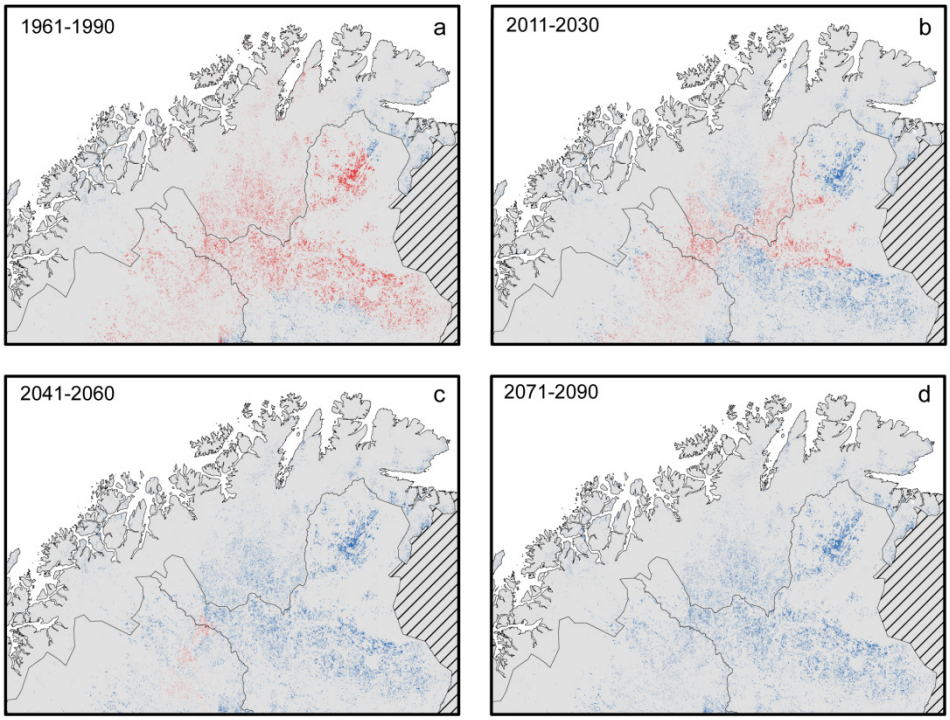

Figure 3. Modeled distribution of dry and moist hummock permafrost mires under projected climate change. Red color indicate dry hummock permafrost mires, blue color indicates moist hummock permafrost mires.

The impact of snow on permafrost mire vegetation

During the seven years that the snow manipulation experiment has been running (starting in 2005) the snow accumulation in the treated plots is approximately twice that of the control plots, with a doubling of the average snow depth in treated plots. In absolute terms the increase is rather modest, with a total increase of snow depth of ~10 cm in the treated plots. This can be compared with snow cover manipulation in other sites where the snow depth is increased by 30 - 280 cm, but often over a shorter number of winter seasons (1-3 years) (Walker *et al.* 1999; Wahren *et al.* 2005; Wipf and Rixen 2010; Natali *et al.* 2011). The signs of permafrost thawing (depressions from ground subsidence as the ice lenses in the peat melt) and the change in plant community structure observed in Storflaket (Johansson *et al.* Submitted) is thus a

result of a modest but long-term manipulation of the snow depth, a realistic simulation of the projected 1-2 cm increase in winter precipitation(Overland *et al.* 2011).

The increased snow depth further results in a delayed snow melt by up to 2-3 weeks in treated in comparison with control plots. This delay in snow melt is however not compensated for by a prolonged snow free season – the timing of snow accumulation in autumn is the same for both treatment and control plots. The delay in snow melt thus cause not only a delay in the onset of growing season, but also an overall shortening of the growing season. Interestingly, the delayed onset and shortening of the growing season did *not* reduce the productivity of the plant community, but rather the opposite. The shortened growing season was compensated for by increased light uptake and photosynthesis rate. Measurements showed significant differences in both light use efficiency and APAR between treated and control plots, where plant communities in the treated plots had higher light use efficiency and APAR throughout the growing season.

Several studies of arctic and subarctic peatlands and tundra ecosystems suggest that the timing of snow melt is a major controlling factor of the annual carbon budget. However, whether the seasonal carbon uptake is directly increased or decreased with the length of the growing season is debated. Positive correlations between the length of the growing season (early snow melt) and the annual or seasonal carbon uptake has been reported by Aurela *et al.* (2004), Grøndal *et al.* (2007) and later Wipf *et al.* (2010) who concluded an overall decrease in community productivity with delayed snow melt. Still, some studies find no such correlation (Parmentier *et al.* 2011) or even the opposite correlation - with earlier snow melt as an effect of snow removal, productivity decreases due to the exposure of plants to low temperatures in the early season (Starr *et al.* 2008).

Our results suggest that the increased photosynthesis with delayed snow melt and shortened growing season is primarily a long-term indirect effect of a change in plant community that has taken place over the years. In the treated plots soil moisture is higher due to ground subsidence and increased water storage from the snow pack. In addition the thicker snow cover has an insulating effect during winter, raising soil temperatures and contributing to a thicker active layer. In these plots there has been a

shift from dry hummock vegetation to moist hummock vegetation, with an increase in abundance of sedges such as *Eriophorum vaginatum* at the cost of dwarf shrubs and lichens. The higher light use efficiency in the treated plots is attributed to the plant species composition, dominated by *E. vaginatum* - not the increased snow depth or prolonged snow duration. In addition it is likely that the increased snow cover have a positive effect on the plant productivity through keeping soil temperatures higher than under ambient snow, allowing for microbial activity during a longer period of the year (Schimel *et al.* 2004; Buckeridge and Grogan 2008; Natali *et al.* 2012). In an environment where plant is nitrogen limited, a change in nutrient availability is likely to affect the plant community structure and productivity.

Suggestions for future research

Paper I and II put the focus on local scale interactions between vegetation and climate in subarctic permafrost peatlands. Together they contribute to increased understanding of the vulnerability of these environments. In paper I the included climate parameter were assumed to play an equally important role. Paper II shows how even a modest increase in snow accumulation has a significant impact on the plant community structure and productivity, within less than a decade of changed precipitation. However, similar, comparable climate manipulation experiments are needed in order to accurately model the impact on vegetation patterns and carbon fluxes in these subarctic peatlands. There are several studies on the impact of warming of air and soil on carbon balance, but to my knowledge fewer on the impact of increased wet precipitation and changes in hydrology with disappearing permafrost, why I suggest particular interest should be put into these topics for future research.

Conclusions

In accordance to my objectives of this study I have investigated climate- vegetation interactions in subarctic peatlands, and its impacts at both a regional and a local level. At the regional level permafrost mires dominated by dry hummock vegetation is under threat of complete disappearance by the ongoing climate change. A transition from dry hummock vegetation to moist hummock vegetation is very likely, with the consequence of increased emissions of methane that offsets the increased carbon uptake from the expansion of vascular plants. At the local level I have presented results that show how even a moderate increase in snow accumulation causes a shift in plant species composition and increased plant productivity over the course of seven years. These results are important since they contribute to a better understanding of climate-vegetation interactions in arctic- and subarctic peatlands under a changing climate. The fact that the permafrost mires in northern Fennoscandia are on the verge of their existence makes them very sensitive to changes and therefore provides an indication of what changes that may be seen at higher latitudes in the future.

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