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Degrading palsa mires in northern Europe:

Changing vegetation in an altering climate and its potential impact on greenhouse gas fluxes

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Abstract

The on-going global warming is projected to have large impacts on the arctic and subarctic environment. Especially vulnerable are ecosystems with narrow climatic envelopes and with small possibilities of adaptation. An example of this is the palsa mires, subarctic mire complexes with patches of permafrost. Palsas are peat mounds with a frozen core, formed by the expansion and upheaval of the segregating ice. Due to the dryer and more nutrient poor conditions on top of the mounds, the palsa vegetation differs from the wet surroundings, creating a mosaic of different microhabitats within the mire. The occurrence of palsas is determined by several environmental and climatological factors, such as air temperature, precipitation, snow depth and peat thickness. Hence, increasing precipitation and air temperature may induce thawing of the frozen peat and subsidence of the peat surface, resulting in a thicker active layer and wetter conditions. Consequently the vegetation may change, adapting to the increased wetness.

This study investigates changes in the vegetational patterns associated with degradation of palsas on a regional scale, and its impacts on greenhouse gas fluxes (GHG). Field observations from fifteen sites in northern Sweden, Finland and Norway showed that the observed vegetational changes related to palsa degradation at the Stordalen mire (northern Sweden) can be considered a general phenomena on a regional scale. Thus the GHG flux measurements from the Stordalen mire may be used to quantify the potential change in GHG fluxes associated with climate induced degradation of palsa mires in the region.

A simple model was built to estimate the areal change in palsa vegetation with a future climate change. The modeling results showed a rapid decrease in areas suitable for palsas within the first 30-60 years: by 2020 the area suitable for palsas was reduced by 50%, and by 2050 no areas suitable for palsas were left. The model projected areas dominated by the dryer palsa vegetation to decrease to the benefit of sphagnum mosses and graminoids, due to the expected increased wetness. The projected impact on GHG fluxes is an increase in both carbon dioxide uptake and methane emissions, mainly due to the expansion of tall graminoid vegetation. Together with similar studies these results may help to indicate what potential impacts a changing climate may have on the distribution of palsa mires. However more research is needed for better understanding the long term vegetational succession in degrading palsa mires and its impacts on GHG fluxes with an altered climate.

SAMMANFATTNING

Med den globala uppvärmningen förutspås klimatet i arktiska och subarktiska miljöer förändras påtagligt. Enligt IPCCs senaste rapport kan både temperatur och nederbörd öka dubbelt så mycket som det globala genomsnittet, och störst ökning väntas under vinterhalvåret. Många känsliga ekosystem och miljöer kommer med stor sannolikhet att påverkas redan vid små förändringar. Ett exempel på sådana miljöer är palsar och palsmyrar. Palsar kan beskrivas som torvkullar med en frusen kärna av torv, is och ibland silt. De bildas i subarktiska myrar genom att den frusna kärnan tillåts växa till under ett antal år med lite nederbörd och låga temperaturer. Palsar är dynamiska system som naturligt växer till och kollapsar och skapar därmed mosaikartade myrmiljöer med hög artrikedom och rikt fågelliv. Med ökande lufttemperatur och nederbörd riskerar palsarna emellertid att tina och kollapsa i snabbare takt än nybildningen vilket skulle leda till att inslaget av palsar i subarktiska myrar blir allt mer sällsynt, något som flertalet studier redan indikerat.

Studier från en palsmyr i Stordalen, strax öster om Abisko i norra Sverige, visar hur vegetationen har förändrats under de senaste trettio åren som en följd av tinande permafrost. I den här studien undersöks i vilken utsträckning dessa förändringar kan anses vara representativa för ett större område. Studien bygger på fältobservationer från femton olika palsmyrar belägna i Sverige, Norge och Finland. De dominerande vegetationstyperna har dokumenterats tillsammans med mätningar av aktivt lager och markfuktighet. Resultatet visar att palsar som tinar och kollapsar generellt följer samma vegetationsmönster som i Stordalen, där vitmossa och gräsarter gynnas av de fuktigare förhållandena. Observationerna visade också en tendens till att upptiningen av palsar är mer utbredd i de västligaste delarna jämfört med palsmyrar belägna länge österut.

En enkel modell utformades för att uppskatta hur stor areal palsmyrar som kan tänkas påverkas av klimatförändringen i framtiden. Enligt modellen kan den nuvarande utbredningen av palsar ha minskat med upp till 50% vid år 2020, beräknat på SCANNETs uppskattning av framtida ökningar av årsmedeltemperatur och årsmedelnederbörd. Till följd av ökad markfuktighet beräknas framför allt gräsvegetationen breda ut sig på bekostnad av de arter som är typiska för palsvegetationen. En effekt av palsmyrarna blir fuktigare och till allt större del utgörs av gräsvegetation är ett ökat utsläpp av metan. För framtida forskning krävs mer kunskap om hur vegetationen i palsmyrar på lång sikt anpassar sig till nya förhållanden, för att med större säkerhet kunna uppskatta den potentiella påverkan på växthusgasutbytet.

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1 INTRODUCTION

The Arctic region is projected to experience significantly larger changes in climate in comparison to the global average. During the last 100 years the average temperature increase in the Arctic Region was almost twice the global average (IPCC, 2007) and simulations from Atmosphere Ocean General Circulation Models (AOGCMs) consistently project the trend to continue. The models produce simulations where mean annual air temperature in the Arctic increase by a factor two and mean winter temperatures by a factor four compared to the global annual mean increase (Christensen *et al.*, 2007). Likewise simulations of precipitation show an increasing trend of both snow fall in winter and rainfall in summer, with the largest increase in winter precipitation (13-36%) (Christensen *et al.*, 2007). Changes of this magnitude will very likely affect special and unique features of the Arctic environment, such as permafrost (i.e. ground that stays frozen for two or more consecutive years) and the life forms associated with it.

Permafrost exists mainly at high latitudes and in mountainous areas where the climate allows the ground to stay frozen all year, with only the uppermost layer thawing during summer (*the active layer*). Permafrost is estimated to cover 24 % of the land surface in the Northern hemisphere (Zhang *et al.*, 1999). In northern Fennoscandia the occurrence of permafrost varies, but most is within the so called discontinuous permafrost zone (Figure 1.1), where the percentage of the land surface underlain by perennial frozen ground varies between 50 and 90% (>90% is defined as continuous permafrost zone) (Nelson *et al.*, 2002). Permafrost may also occur far outside the discontinuous zone. Where the regional climate is not favourable, topographic and geomorphologic variations at a local scale, such as mountains, high plateaus, mires etc. may create suitable conditions for permafrost to form within smaller areas or in separated patches (King, 1986; Seppälä, 2005; Johansson M. *et al.*, 2006), in the so called sporadic permafrost zone (10-50% permafrost coverage). This demarks the border of the climate envelope for the existence of permafrost. Further south or west permafrost does not occur except at high altitudes or under very specific conditions in small isolated patches (<10% areal coverage) (King, 1986, Nelson *et al.* 2002).

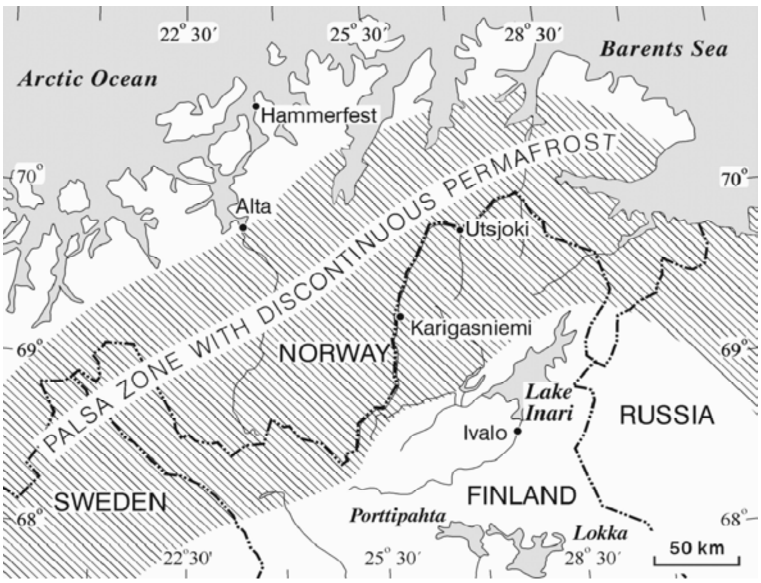

Figure 1.1 Overview map of the discontinuous permafrost zone in northern Fennoscandia. (Seppälä, 2006)

Where permafrost exists at its margins it is very sensitive to changes in climate and environment (Fronzek *et al.*, 2006; Parvainen and Luoto, 2007; Sollid and Sørbel, 1998). A small increase in summer air temperatures may result in a mean annual ground temperature above freezing, a thicker snow cover may reinforce the insulating effect during winter, preventing the permafrost to be preserved or develop deeper into the ground. As a consequence, the occurrence of permafrost features such as peat plateaus and *palsas* (peat mounds with a frozen core) are threatened by the global warming and expected to decrease dramatically during the next 100 years (Fronzek *et al.*, 2006). As climate becomes warmer and wetter, the climatic envelope for permafrost in the Nordic region will likely be shifted further north-east. However, the occurrence of palsas does not necessarily follow this shift, since peat thickness, vegetation cover and snow depth are other important factors for palsa development (Seppälä, 1982a, 1986, 2005, Johansson M. *et al.*, 2006; Fronzek *et al.*, 2006, Zuidhoff and Kolstrup, 2005).

Since the 1980s temperatures at the top of the permafrost have increased by up to 3 °C in the Arctic, and signs of permafrost thawing have already been observed (Solomon *et al.*, 2007). Besides environmental changes, thawing permafrost serve as a source of greenhouse gases (*GHG*). When the active layer becomes thicker, both carbon dioxide and methane is released when the peat is decomposed. The potential effect of global warming is not well quantified yet (Solomon *et al.*, 2007) but studies of already degrading permafrost in the sporadic and discontinuous zone may help to understand and quantify what possible future changes in GHG fluxes to expect as larger areas of frozen peat starts thawing.

2 HYPOTHESIS AND OBJECTIVES

Several studies have been conducted on GHG fluxes associated with thawing permafrost at the Stordalen Mire, Abisko, Sweden (Malmer *et al.*, 2005; Christensen *et al.*, 2004; Johansson M. *et al.*, 2006; Johansson T. *et al.*, 2006). The general conclusion of these site specific studies is that changes in wetness and species composition can be observed as a direct consequence of the thawing peat. Consequently, more carbon is released and the flux rates of carbon dioxide and methane are altered.

The hypothesis is that similar changes in wetness and species composition in subarctic mires are taking place elsewhere in the discontinuous/sporadic permafrost zone due to degrading and thawing permafrost, and that the results on GHG fluxes from the Stordalen mire are indeed applicable at a larger scale.

The main objective of this study is to upscale the flux measurements from Stordalen to a regional level, in order to quantify what potential effect global warming may have on GHG fluxes from palsa mires. However, in order to apply the results from Stordalen, the hypothesis must first be tested and verified. The study can thus be separated in two parts:

1. Verifying the hypothesis. This is done *in situ* by investigating whether the vegetational patterns and changes in surface structures observed at the Stordalen mire is a general phenomena, applicable to other subarctic mires in northern Fennoscandia.

2. Depending on the extent to which the hypothesis can be verified, the flux measurements are up-scaled to an area covering the northernmost parts of Norway, Sweden and Finland. The total change in GHG fluxes, induced by warming temperatures and increased precipitation, are computed for three different time horizons: 30 years, 60 years and 90 years ahead (using the year of 1990 as baseline).

3 BACKGROUND

3.1 THE LIFE CYCLE OF PALSAS

In the discontinuous and sporadic zones permafrost can be found particularly in ombrotrophic[1] mires with sparse vegetation and a relatively thick peat layer that can act as an insulator for the frozen ground during summer (Seppälä 1982a; 1986; Johansson M. *et al.*, 2006). In addition to the peat cover, climate and hydrological conditions are also essential for the development of palsas. The air temperatures must be low (in principal mean annual air temperature below freezing) for the ground to stay frozen year round, but the amount of precipitation is perhaps even more pivot. Palsas require little precipitation; optimally less than 400-500 mm yr^{-1} (Luoto *et al.*, 2004a). In wintertime the snow cover must be thin in order to allow heat transport away from the ground and segregated ice to form (Seppälä, 1982a; Seppälä, 1986; Johansson M. e*t al.*, 2006). Palsas are therefore often found in larger mires and wetlands, free of dense forests where the wind exposure and snow drift leaves the ground with a very thin or even lacking snow cover (Luoto and Seppälä, 2002). A high level of precipitation during summer is disadvantageous for palsa formation, since wet peat has much higher heat conductivity than dry peat, enhancing thawing of the frozen core (Seppälä, 1982a; 1986, Kajula *et al.*, 2008). On the contrary saturated peat is beneficial during autumn, when air temperature is colder and freezing period starts (Seppälä, 1986).

Figure 3.1 Snow free palsa in Vaisejeäggi mire, Finland 1994. Photo by Matti Seppälä (Seppälä, 2006)

A series of relatively cold years with little precipitation may result in patches where the frozen ground is not completely thawed during the summer. A frozen core, constituted by a mix of peat (and in some cases silt material) and segregated ice, is built up in these patches. The expansion of

[1] Ombrotrophic: Mire system that is fed by rain water. "ombrotrophic" *A Dictionary of Ecology*. Michael Allaby (ed). Oxford University Press, 2006. Oxford Reference Online. Oxford University Press. Lunds universitet. 20 October 2008 <http://www.oxfordreference.com.ludwig.lub.lu.se/views/ENTRY.html?subview=Main&entry=t14.e3923>

the segregated ice (fed by adjacent unfrozen water) causes the ground to heave above the surrounding, forming an embryo of a palsa. The upheaval of the ground further increases the wind exposure and intensifies the effect of snow drift, enhancing the permafrost to develop further (Seppälä 1982a; 1986; Zuidhoff and Kolstrup, 2005). As this process continues palsa formations such as large peat plateaus (covering hectares) and smaller (a few meters in diameter) oval-, dome- or string-shaped mounds are developed. The height of palsas vary, but may reach up to 10 m in the mature stage, plateaus being somewhat lower (Seppälä, 2005). The wind exposure and nutrient poor conditions on top of the palsas create a harsh environment for vegetation. Mature palsas is dominated mainly by mosses and lichens and a field layer of dwarf shrubs such as *Empetrum hermaphroditum* and low plants of *Betula nana*. *Rubus chamaemorus* is also common since it is tolerant to the dry conditions, hard winds and frost (Zuidhoff and Kolstrup, 2005). The low, dense vegetation of mosses and dwarf shrubs are good insulators in summer and prevents rain to infiltrate the peat layer, conducting heat to the frozen core. In winter the low vegetation facilitates snow drift, leaving the ground bare and exposed to the cold air (Zuidhoff and Kolstrup, 2000; 2005; Johansson M. *et al.*, 2006).

As palsas grow larger, cracks begin to form in the peat layer and large peat blocks slides down along the sides. In this way the frozen core becomes exposed to the surrounding water pools, which enhances thawing and degradation (Sollid and Sørbel, 1998; Seppälä, 1986; Zuidhoff, 2002; 2003). Barren peat may be exposed on large parts of the palsas without any vegetation, while in other parts, mainly slopes and depressions, dwarf shrubs such as *Betula nana* may grow larger and higher, facilitating snow to accumulate during winter and further enhance the thawing process. This degradation process causes the palsa to collapse, leaving remnants such as peat ridges, *thermokarst ponds* (open water pools), depressions and smaller mounds (*pounus*) (Zuidhoff, 2003; Zuidhoff and Kolstrup, 2005; Seppälä, 1986). The process then starts over and after some time, when enough peat has accumulated, new palsas may develop where the old collapsed were to be found.

Figure 3.2 Signs of mature and degrading palsas. Cracks in the surface peat (left) and peat block erosion (above) in Stuorajavvri, Norway. Photo by Julia Karlgård (2008)

Both the formation and degradation of palsas are natural cyclic processes where climate and environmental conditions are favourable, and in a given mire there may be several palsas and plateaus in different stages of the life cycle. Thus palsa mires are often forming a mosaic of different micro environments, providing habitats for a wide range of life forms and serve as important breeding spots for many bird species (Luoto *et al.*, 2004b). However, when air temperature and/or precipitation increases, the balance between degradation and new formation of palsas will likely be altered so that more palsas are collapsing than are being formed, resulting in changing surface structures, hydrological conditions and vegetation. This has been observed in palsa mires both in Finnish Lapland (Luoto *et al.*, 2004b; Luoto and Seppälä, 2003; Seppälä, 2005), northern Sweden (Zuidhoff, 2002; Zuidhoff and Kolstrup, 2000) and Norway (Sollid and Sørbel, 1998; Hofgaard, 2003) and is also subject of the present study.

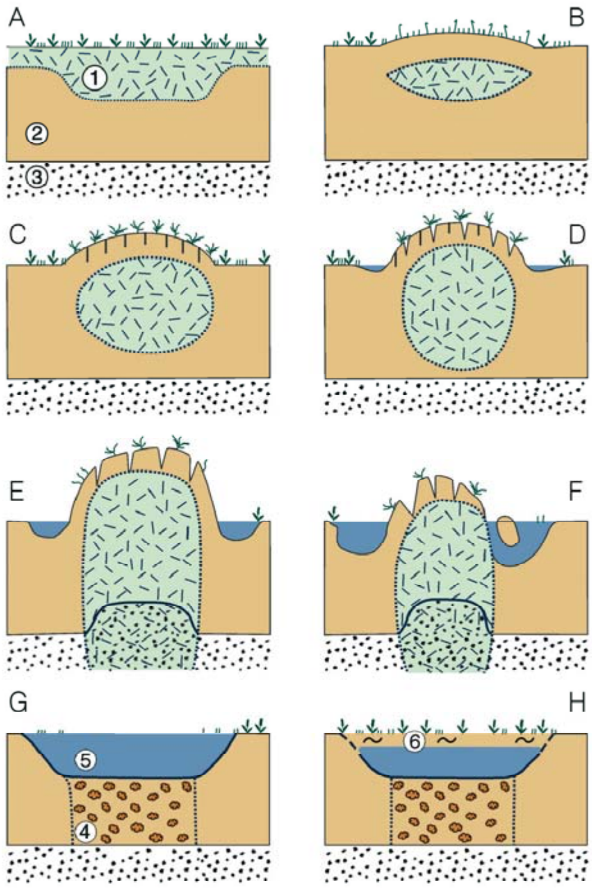

Figure 3.3 Cyclic development of palsas in a peat bog. **A**: In the beginning of the thawing season the surface layer is frozen (1). **B**: In the end of the thawing season a frozen core is left, covered by peat (2). **C**: Expansion of the ice creates a palsa embryo. **D**: Young palsa, cracks in the surface peat begin to develop. **E**: Mature palsa with sparse vegetation on top. Frost penetrates down to the underlying silt sediment (3). **F**: Collapsing palsa. **G**: Palsa is completely thawed and the peat is decomposed (4), leaving a circular pond with open water (5). **H**: New peat is formed (6). (Seppälä, 2006)

3.2 VEGETATIONAL CHANGES RELATED TO PERMAFROST DEGRADATION

For many decades palsas and permafrost have been studied throughout northern Fennoscandia. One of the most intensely studied areas is the Stordalen mire, located 10 km east of Abisko, Sweden (68°21'N, 18°49'E) and ca 200 km north of the Arctic circle. Regular measurements of air temperatures and precipitation have been conducted since 1913 at the Abisko Scientific Research Station, and studies of vegetation related to permafrost formations extend back to 1970. It is therefore possible to study long term changes in thawing permafrost in relation to climate variations, and its impacts on plant communities in the area.

Malmer *et al.* (2005) conducted a comparative study of the vegetation and surface structures on the Stordalen mire between 1970 and 2000. Using aerial images and ground surveys of plant communities the study revealed two major processes that had taken place during the last three decades: the dryer sites dominated by ombrothrophic hummock vegetation such as mosses and evergreen dwarf shrubs had receded, while the wet sites, dominated by minerotrophic vegetation such as tall graminoids, had expanded (Christensen *et al.* 2004; Malmer *et al.*, 2005; Johansson T *et al.*, 2006). This trend of degrading hummock areas becoming wetter is also confirmed by Zuidhoff (2003).

These changes in vegetation and surface structures directly lead to changes in carbon uptake, sequestration and release. The carbon flux depends on several parameters such as hydrology, soil conditions and species composition and can therefore differ significantly between vegetation types and surface features and also within a mire. In the dryer hummock areas both carbon uptake and litter formation is relatively small due to little biomass. Also, the litter from *Sphagnum* and hummock mosses are very reluctant to decomposition, which leads to a relatively large proportion (≈ 50%) of the carbon litter reaching the anoxic catotelm[2]. The decay rate in the catotelm is about three orders of magnitude lower than in the aerobic acrotelm (Malmer *et al.*, 2005), and the undecomposed litter form peat. This accumulation of organic material serves as a carbon sink as long as the decomposition is slow and the peat stay frozen. When the active layer becomes thicker due to thawing, the volume of soil carbon (peat) available for decomposition increases. The decomposition of peat releases both carbon dioxide and methane, but since the active layer now becomes thicker and exposes more unfrozen peat, a larger portion is decomposed in the catotelm (Anisimov, 2007).

The carbon uptake from tall graminoid vegetation is significantly larger than that of moss and lichen hummock vegetation, and >95 % of the litter decay is allocated to the aerobic acrotelm (Malmer *et al.*, 2005). Hence, the CO_2-flux is considerably higher in tall graminoid areas than in hummock or semi-wet areas (Johansson T. *et al.*, 2006). The net effect of carbon uptake and carbon release (autotrophic and heterotrophic respiration) is negative, i.e. the tall graminoid vegetation is a CO_2-sink during the growing season. However, as a consequence of thawing or even lacking permafrost, the active layer is generally thicker in tall graminoid dominated areas (Åkerman and Johansson, 2008; Johansson T. *et al.*, 2006). Moreover, these sites are often waterlogged due to the subsidence of the ground caused by permafrost degradation. This leads to increased anaerobic decomposition and methane production, hence the release of methane at these sites is very high in comparison to the hummock sites (where there may even be a net CH_4-flux uptake). Converting the flux measurements of CH_4 to CO_2 equivalents, the methane release is over-balancing the net effect of carbon dioxide uptake in the tall graminoid vegetation areas (Christensen *et al.*, 2004; Johansson T. *et al.*, 2006). The thawing permafrost and degrading palsas therefore has, in spite of the largely increased CO_2 uptake by tall graminoids, a positive radiative forcing effect, i.e. more GHG is being released to the atmosphere than what is taken up by the ecosystem (Johansson T. *et al.*, 2006).

While the studies by Malmer *et al.* (2005), Johansson T. *et al.* (2006) and Christensen *et al.* (2004) investigated the GHG fluxes during growing season, recent studies by Bäckstrand (2008) and Jackovitz-Korchinsky (*pers. com.*) have focused on the annual fluxes in the same area. These studies confirms the strong positive radiative forcing effect as a result of dryer palsa areas turning wetter due to thawing permafrost, and the results from annual GHG flux measurements will here be used to upscale and quantify the potential change in GHG fluxes due to thawing palsas.

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[2] Catotelm: The lower layer of a peat bog where organic matter is decomposed anaerobically at a much slower rate than the aerobically decomposition in the upper acrotelm ("acrotelm" *A Dictionary of Ecology*. Michael Allaby (ed). Oxford University Press, 2006. *Oxford Reference Online*. Oxford University Press. Lunds universitet. 11 October 2008 <http://www.oxfordreference.com.ludwig.lub.lu.se/views/ENTRY.html?subview=Main&entry=t14.e55>

4 Study Area

The study area covers the northernmost parts of Norway, Sweden and Finland respectively. The land cover map used for up-scaling the GHG fluxes stretches from 15°45'E to 30°57'E, and from 67°21'N to 71°25'N (Figure 4.1), but due to lack of data the north-western part of Russia is not included (Johansen, *pers. comm.*). Since the study extends over large areas in both east-western and south-northern direction, topography, climate and vegetation vary widely within the region. The south-western part of the study area is made up by the Scandes Mountains and the west coast of Norway, with a pronounced maritime climate and a landscape characterized by the many fjords (Tikkanen, 2005; Corner, 2005). Vegetation is here predominantly boreal, mainly constituted by birch and pine forest (Heikkinen, 2005). The central area of the study region is located east of the Scandes mountains with landscape formed by moderately steep slopes in the west and lower hills towards the east. In the border between the treeless alpine zone in the western mountains and the more productive lowland forests in the east, a narrow band of mountain taiga is formed, extending in the north-south direction. This mountain taiga is dominated by Scots pine (*Pinus sylvestris*) and Norwegian spruce (*Picea abies*) (Kullman, 2005). In the central and eastern parts of northern Sweden and most parts of northern Finland the large forests are featured by rivers, lakes and the rich abundance in mires and wetlands (Kuusisto, 2005; Pajunen, 2005). More than 90 percent of all palsa mires in the region are located east of the mountain range (Luoto *et al.*, 2004a). Further northeast and at higher altitudes the vegetation is dominated by birch and heath vegetation.

Figure 4.1 Red frame demarks the study area. Projection used is WGS 84 UTM Zone 34 N. Data © ESRI, 2005.

From the southwest towards the northeast the climate changes from highly maritime to more continental-like. Mean annual air temperatures range from +2°C to -4°C, with the highest temperatures along the west coast of Norway. The lowest mean annual temperatures are found in central Finnmark (northern Norway) and northernmost parts of Finland. Similar to temperature patterns, precipitation is highest along the Norwegian northwest coast and lowest in the inner parts of Finnmark (Norway) and in the rain shadow east of the mountain range, ranging from over 1200 mm to less than 300 mm of annually accumulated precipitation (Tikkanen, 2005).

The visited sites are located mainly in the western and central parts of the study area (Figure 4.2). The physical properties such as location, elevation and climate are described in Table 4.1. Based on previous studies a brief summary of the sites' characteristics is presented in Table I, Annex I.

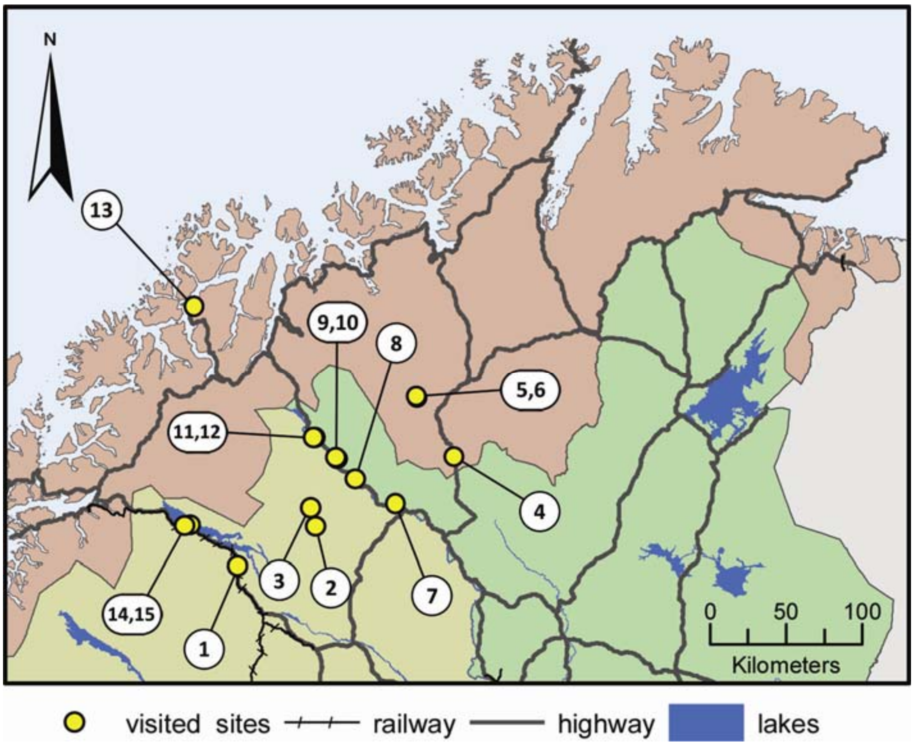


Figure 4.2 The study area covers northern Norway, Sweden and Finland (Russia is not included). Study sites presented in yellow. Projection used is WGS 84 UTM Zone 34 N. Data © ESRI, 2005.

Table 4.1 List of visited sites. Geographic coordinates and elevation is measured at the sites with GPS (using WGS84 as geographic reference). MAAT and MAAP data is based on reference normal values (1961-1990) from the nearest climate station(s). Temperature values are estimations, computed in relation to the difference in altitude between the site and the climate station. An average air temperature lapse rate of -0.65°C per 100 m rise is used, according to the international standard (Ahrens, 2003). The stations used for climate data are given in brackets. Where more than one station is listed, temperature and precipitation are calculated as mean values of the stations. Numbered index refers to the source of data ([1]Alexandersson *et al.*, 1991/SMHI, 2008; [2]DNMI, 2008; [3]Kilpisjärvi Biological Station, 2008). The mire size is estimated from NORUT land cover map.

Nr	Site (Climate stations)	Latitude Longitude	Elevation (m)	Size of mire (ha)	Estimated MAAT (°C)	Estimated MAAP (mm yr^{-1})
1	**Rensjön-Bergfors** (Rensjön[1], Bergfors[1])	68 07 19 19 49 46	-	113	-1.7	420
2	**Järämä** (Kattuvuoma[1], Karesuando[1], Naimakka[1], Kummavuopio[1])	68 19 09 21 03 58	514	35	-3.4	433
3	**Tavvavuoma** (Kattuvuoma[1], Karesuando[1], Naimakka[1], Kummavuopio[1])	68 28 07 20 59 18	580	45	-3.8	433
4	**Aiddejavvre** (Sihccajavri[2])	68 44 27 23 14 33	368	75	-3.0	366
5	**Stuorajavvre** (Kautokeino[2], Bidjovagge[2])	69 06 25 22 44 26	396	160	-3.2	408
6	**Stuorajavvre (small)** (Kautokeino[2], Bidjovagge[2])	69 06 56 22 43 26	402	20	-3.2	408
7	**Markkina** (Karesuando[1])	68 29 10 22 18 04	332	300	-2.3	415
8	**Pättikkäkoski** (Naimakka[1])	68 38 02 21 42 04	406	50	-2.8	410
9	**Saukkokoski S** (Kummavuopio[1], Keionovuopio[1], Naimakka[1])	68 45 12 21 24 49	418	15	-2.9	410
10	**Saukkokoski** (Kummavuopio[1], Keinovuopio[1], Naimakka[1])	68 45 42 21 23 40	421	75	-2.9	410
11	**Keinovuopio** (Kilpisjärvi[3], Kummavuopio[1], Keinovuopio[1], Naimakka[1])	68 52 52 21 01 57	468	20	-2.7	434
12	**Peera** (Kilpisjärvi[3], Kummavuopio[1], Keinovuopio[1], Naimakka[1])	68 53 04 21 03 15	471	5	-2.7	434
13	**Tromsö Camping** (Tromsö[2])	68 38 50 19 00 03	10	1	3.2	1000
14	**Stordalen** (Abisko[1])	68 21 12 19 08 31	360	50	-0.6	304
15	**Storflaket** (Abisko[1])	68 20 53 18 58 11	402	25	-0.9	304

5 METHOD

5.1 FIELD OBSERVATIONS

In order to document the current state of the sites (vegetation types, surface structures, palsa features etc.) for comparison with the observations from Stordalen, field observations were made. Because of the limited time of the project, changes in vegetation cannot be studied but only the present state. However, by combining different methods and strategies, the site observations can be related to plausible changes in the past, in order to compare with the observed vegetational changes in Stordalen:

- *The visited sites were chosen based on previous knowledge of the occurrence of permafrost*. This means that permafrost formations such as palsas or peat plateaus have been observed and documented at all sites in previous studies. However, since there is no single study of the distribution and degradation of palsas that covers the whole region or the same time period, the documentation at each site differs widely in time, quality and quantity.

- *The life cycle stage of the palsas was attempted to be identified.* Although the stage of the palsa does not give any direct information of the age of the palsa (Luoto and Seppälä, 2003; Zuidhoff and Kolstrup, 2000; Nihlén, 2000), it can give information on what possible changes and processes that may have taken place over the past years. In order to identify the palsa's stage of development, features such as form, height, cracks in the peat layer, thermokarst ponds and vegetation cover was used as indicators, similar to the strategy developed by Zuidhoff and Kolstrup (2005) and Zuidhoff (2003). The method of using thermokarst ponds as indicators of former presence of palsas has been studied by Luoto and Seppälä (2003)

- *The vegetation was recorded by using the same classification of vegetation types as described in Malmer* et al. *(2005)*. This method assumes that the composition of plant species in other palsa mires can be categorized by following the same scheme of vegetation classes as used at the Stordalen mire. If vegetation patterns in other areas differ from that at the Stordalen mire, the categorization by Malmer *et al.* (2005) would be unsuitable, demonstrating the assumption to be incorrect. The classification scheme is described in Annex I, Table II.

Based on previous documented occurrence of palsas, thirty-one sites were selected to be visited throughout the region. However, some of the sites were situated far from the main road and many tracks in the road map turned out to be snowmobile tracks or simply unsuitable for car transportation. Therefore only fourteen of the originally thirty-one sites could be investigated. One additional site was unexpectedly found in Tromsø and was added to the list of visited sites.

Each site was documented by photographs and the following was recorded:

- Coordinates in latitude/longitude, using WGS84 as geographical reference system
- Altitude (meters ASL)
- Site characteristics such as type of permafrost feature (palsa, pounus or peat plateau) and surrounding environment (hills, forest, lakes, rivers *etc.*)
- Height and size (diameter) of palsa features.
- Active layer thickness (using a metal rod, length 1 m) and soil moisture content (using a Theta Probe ML2) on hummocks
- Dominating vegetation type
- Functional groups and major species.

Preferably measurements of the active layer thickness (ALT) and soil moisture content (SMC) should have been taken evenly distributed throughout the whole mire. But since most of the mires were dominated by wet or semi-wet vegetation and these areas are difficult to enter by foot it was not possible to make measurements representative of the whole mire, but only along the edges where the ground was stable enough to support a person. Also, where measured, it turned out that the active layer thickness in wet and semi-wet areas was thicker than 1 m (the metal rod was too short to reach down to the frozen layer). Because of the large portion of wet/semi-wet areas in relation to hummock areas, the method of evenly distributed sampling points would therefore result in an ALT > 1 m at many of the sites. In order to record also the active layer thickness in more detail on the hummock areas ALT was assumed to be equal to or larger than 1 m elsewhere. Still, it is a rough estimate, but since the main interest of this work lies in changes in the hummock areas, this assumption is considered acceptable.

For the same reasons the soil moisture content was not recorded in wet or semi-wet areas where the theta probe measured the soil moisture content as “above table”. At two sites (Rensjön-Bergsjön and Järärmä) heavy rains during the days of measurements may have given rise to overestimated SMC values, and must therefore be treated with caution since these measurements may not be representative for the sites.

The dominating vegetation types of the mire were established by first determining the predominant vegetation in hummock areas and wet/semi-wet areas separately and thereafter determine whether the mire was wet-dominated or hummock-dominated. In this way it is also possible to compare and couple measurements of active layer thickness and soil moisture content with the hummock vegetation types. In the plant species composition survey made at Stordalen in 2000 (Malmer *et al.*, 2005) the mire vegetation was categorized in four major classes, following a wetness gradient; *dry hummock* vegetation, *moist hummock* vegetation, *carpet vegetation* and *tall graminoid* vegetation. This categorization is also used in the present study to describe the vegetation at the visited sites. A detailed description of the vegetation classes are found in Appendix I, Table II.

Dry hummock vegetation was divided into two subclasses based on the dominant species in the bottom layer: lichen hummock vegetation and moss hummock vegetation. The two hummock types was differentiated from each other since it was noted that lichens have increased at the expense of mosses and dwarf shrubs on hummock sites from 1972/73 to 2000. This shift in hummock vegetation may be explained by higher spring temperatures that cause the snowmelt to set off earlier and expose the vegetation to frost draught, something that favours the expansion of lichens (Malmer *et al.*, 2005). In the flux analysis, however, moss and lichen hummocks are not differentiated from each other.

The visited sites in the present study often contained a significant portion dominated by tall and dense shrubs and could not be accurately classified neither to hummock vegetation nor carpet or tall graminoid vegetation. Therefore *tall shrub vegetation* is here treated as a separate (fifth) class, but rather for the purpose of describing the site properly than for the GHG flux calculations.

Figure 5.1 Moist hummocks covered by mosses and *Rubus chamaemorus* (Cloudberries) in Peera, Finland. The area of moist hummock vegetation is here a transition zone between the dry hummock vegetation (not in the picture) and carpet vegetation (dense green carpet of *Sphagnum*). Tall graminoid vegetation is visible in the background. Photo by Julia Karlgård, 2008.

5.2 RELATING OBSERVATIONS TO CLIMATIC FACTORS

The observations of vegetation and surface structures in the mires were compiled together with data of mean annual air temperatures (MAAT) and accumulated annual precipitation from the sites (MAAP). The climate data used was normal values from the period 1961-1990, taken from the Swedish Meteorological and Hydrological Institute (SMHI) and the Norwegian Meteorological Institute (DNMI). However, since the study sites were not always situated very close to a meteorological station, average values of the two or three nearest meteorological observation stations were computed. A lapse rate of -0.65 °C per 100 m rise accounts for differences in elevation. Also meteorological measurements from the research station in Kilpisjärvi (Finland) were used for the sites located along the Torne River.

In order to study the link between vegetational patterns and climate, the climate suitability for palsas to occur was studied for each site. Fuzzy membership values describing the climate suitability were computed for each site, based on the estimated MAAP and MAAT. The climate suitability (i.e. fuzzy membership) computations were based on two probability curves produced by Luoto *et al.* (2004a). In the study by Luoto *et al.* (2004a) the distribution of palsa mires in northern Fennoscandia was modelled based on several climatological variables, including MAAT and MAAP. The climatological variables were used to compute the probability of palsa occurrence for each square in a grid covering northern Europe. Figure 5.2 illustrates the relationship between the modelled probability of palsa occurrence and the two climatological variables MAAP and MAAT. In the present study these probability curves are transformed and rescaled to fuzzy membership curves, reaching from zero (low climate suitability) to one (high climate suitability). Maximum suitability is set to 1 where the curve peaks or probability of occurrence reaches 1. The procedure for computing the climate suitability is described in Annex II.

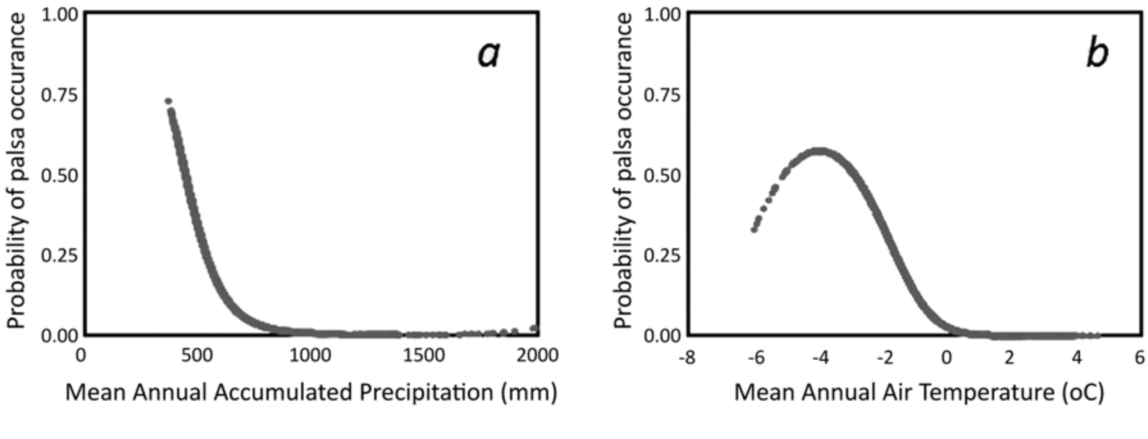


Figure 5.2 Relationship between the modelled occurrence of palsa mires and (***a***) mean annual accumulated precipitation (***b***) mean annual air temperature (Luoto *et al.*, 2004)

By comparing the total climate suitability μ_{tot} with dominating vegetation types, active layer thickness, and soil moisture content, possible links between wetness, vegetation and climate can be studied.

5.3 ANALYSIS: CHANGES IN LAND COVER TYPES AND GHG FLUXES

For the up-scaling process a 1 ha resolution land cover map was used. The map was produced by the Northern Research Institute (NORUT) in 2006 (Johansen, *pers. comm.*) and covers the northernmost parts of Sweden, Norway and Finland, an area of approximately 270 000 km^2. The land cover map was derived using Landsat TM/ETM+ images from the period 1994-2002, several digital elevation models and digital topographic maps with information on forests, mires, agricultural areas, waters etc. The NORUT land cover map contains a total of 34 classes, including a few non-vegetational classes such as agricultural land, impediment, waters, bedrocks and glaciers. The vegetation class used in the present analysis is the so called hummock mire complex class (Figure 5.3). Table II (Annex I) compares the description of the vegetation types defined by Malmer *et al.* (2005) with that of the corresponding vegetation classes in the NORUT land cover map.

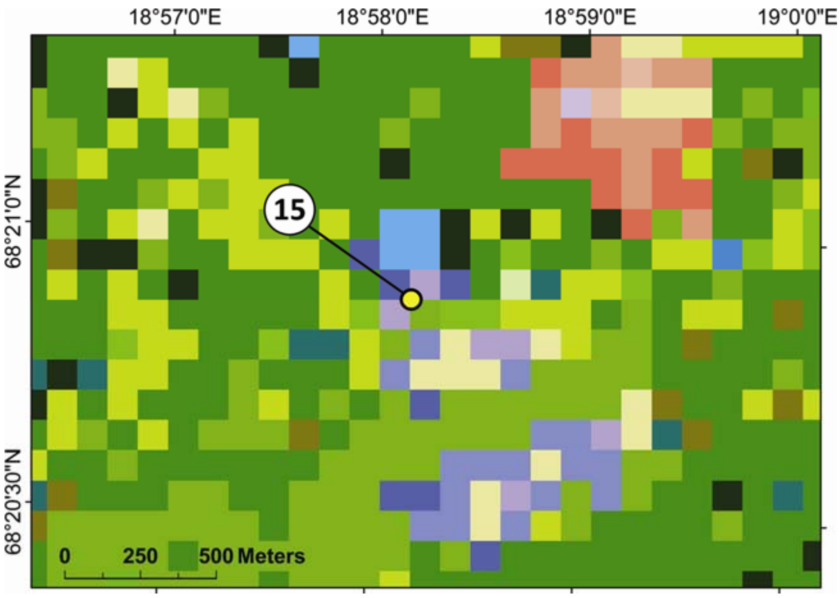


Figure 5.3 Example of NORUT landcover map showing the area surrounding one of the sites (Storflaket, nr 15). Bright violet colour represents hummock mires.

Climate maps of MAAT and MAAP reference normal values (1961-1990) was obtained from The Swedish Meteorological and Hydrological Institute *SMHI* (Wingqvist, *pers. comm.*.), The Norwegian Meteorological Institute *DNMI* (DNMI, 2008) and The Finnish Meteorological Institute *FMI* (Pirinen, *pers. comm.*). For the FMI data 1971-2000 is used as reference normal period. Since the maps differed in data format, level of detail and reference system they were homogenized to raster maps with a spatial resolution of 1km^2 and reference system WGS84 UTM Zone 34N (the same used in the NORUT map). Climate maps from SMHI and FMI were originally in vector format and were therefore rasterized using spline interpolation in ESRI ArcMap. The level of detail was 0.1°C for MAAT and 1 mm for MAAP.

The potential change in GHG fluxes was calculated by estimating the areal change in the hummock mire complex (HMC) class induced by increased temperature and precipitation. A combination of linear regression for climate change and a so called climatic envelope technique (Heikkinen *et al.*, 2006) for the ensuing vegetational changes was used in the model. The process can be described in four major steps (see also detailed flow chart in Annex II, Figure I-III), all performed by Idrisi 15.0 (Andes edition):

1. *Initial reclassification*. Since the HMC class originally covered both dry hummock and moist hummock areas (Table II, Annex I), it was necessary to differentiate between moist hummock and dry hummock pixels before applying the climate change scenarios. This differentiation was done by using the MAAT and MAAP of 1961-1990 normal reference values to compute the climate suitability value of every HMC pixel. Based on field observations each of the four vegetation classes (*dry hummock, moist hummock*, *carpet* and *tall graminoid* vegetation) was assigned a climate suitability interval (Table 5.1) and the HMC-pixels were then reclassified accordingly.

2. *Modelling future climate*. According to the Scandinavian/North European Network of Terrestrial Field Bases (SCANNET), Regional Atmospheric Ocean General Circulation models (AOGCMs) project increasing MAAT and MAAP by +0.35-0.4 degrees/decade and +1.5-2 percent/decade respectively, based on several scenarios, including SRES A2 and B2 (Sælthun and Barkved, 2003). Similar rates of increase are reported by Arctic Climate Impact Assessment (ACIA) (Huntington *et al.*, 2005). Applying these projected rates to the 1961-1990 normal reference values of MAAT and MAAP, minimum and maximum climate scenarios were projected for three time periods with 30 years interval: 2020, 2050 and 2080 (Table 5.2).

Table 5.1 Relation between vegetation class, climate suitability and GHG flux rates. Flux rates from Bäckstrand (2008).

	dry hummock	moist hummock	carpet	tall graminoid
climate suitability:	> 0.4	0.2-0.4	0.01-0.2	<0.01
CO_2 flux rate: ($g\ C\ m^{-2}\ yr^{-1}$)	29.7	-2.8*	-35.3	-34.9
CH_4 flux rate: ($g\ C\ m^{-2}\ yr^{-1}$)	0.5	3.35*	6.2	31.8

*Calculated average between dry hummock and carpet vegetation

3. *Modelling future vegetation changes*. Changes in vegetation types were determined by the change in climate suitability. For every 30 yr period the climate suitability was computed for all pixels that originally belonged to the HMC class. The pixels were then assigned the vegetation type associated with the climate suitability value, similar to step 1.

4. *Computing changes in GHG fluxes.* The change in GHG fluxes were computed based on the occurrence of vegetation types in the different scenarios. CO_2 and CH_4 flux rates used for the computations are yearly average values (Bäckstrand, 2008) displayed in Table 5.2. As a reference the total GHG fluxes was computed for the 1961-1990 scenario: for every pixel originally belonging to the HMC class the GHG flux was calculated, with flux rates determined by the vegetation class derived in step 1 (Table 6.1). In the future scenarios (minimum and maximum increase of MAAT and MAAP for 2020, 2050 and 2080, see Table 5.2.) the GHG fluxes was calculated according to the new distribution of vegetation classes derived in step 3.

Table 5.2 Projected changes in MAAT and MAAP relative to the reference normal values (1961-1990) for three time periods: +30 years (2020), +60 years (2050) and +90 years (2080).

Year:	2020		2050		2080	
	Min.	Max.	Min.	Max.	Min.	Max.
Δ temp (°C)	1.05	1.2	2.1	2.4	3.15	3.6
Δ precip (%)	4.5	6	9	12	13.5	18

6 RESULTS

6.1 FIELD OBSERVATIONS

The field observations confirm that the changes in surface structures and vegetational patterns associated with degrading permafrost on Stordalen mire represent general phenomena within subarctic mires in the studied region. All of the four (five including tall shrub) vegetation types defined by Malmer *et al.* (2005) were recorded, often all together at one site, and there was no need to modify the classification scheme or complement with a new class. The results from GHG flux measurements from Stordalen (Bäckstrand, 2008) are thus considered to be applicable at a larger scale and may well be used for up-scaling GHG flux measurements from Stordalen mire to other palsa mires in northern Fennoscandia. Instead of presenting the results from measurements and observations from all sites, this section is focused on the key findings. A full presentation of the field observations is found in Table III-IV, Annex I.

When comparing the observations from the different sites, a relationship between the development stage in palsas and their location in the east-western direction can be noticed. Generally palsas and peat plateaus are higher (> 2 m) with a relatively thin active layer (indicating a mature state) in the easternmost located sites, while in the western parts of the study area hummocks are lower, often dominated by moist or wet vegetation and with a thicker active layer (> 1 m). No signs of new formation of palsas were observed in any of the visited sites.

The relationship between palsa development and geographical location is illustrated in Figure 6.1. Active layer thickness and palsa height is plotted for a number of sites along a west-east gradient. In order to avoid possible influences from a north-south gradient, sites located north of the eastern-most site (Aiddejavvre) are not included in the diagram. The gradient stretches from 18°58'E to 23°15'E (approximately 178 km) and from 68°07'N to 68°44'N (circa 73 km).

A similar comparison of the vegetational patterns and soil moisture content in the hummock-dominated areas also reveals a trend of increasing wetness in the western direction (Figure 6.2), in agreement with the observed thicker active layers and lower palsa heights. Hummock dominated sites are more frequent in the north-east, whereas the western sites are dominated by wet and semi-wet vegetation. Likewise, the hummock vegetation at the eastern sites is mainly moss- or lichen dominated, while moist hummock vegetation is predominant in the western sites. The site characteristics are summarized for all locations in Table III, Annex I. Figure 6.3*a-b* illustrate the difference between moist hummock vegetation in the western part of the study area and dry hummock vegetation at a site located 180 km further east.

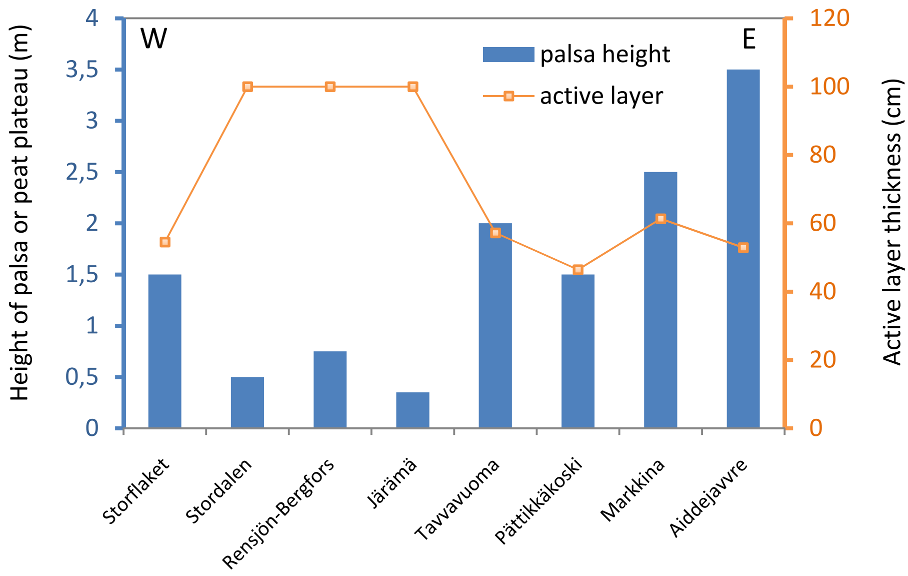


Figure 6.1 Palsa height and active layer thickness compared for a selection of sites in the east-western direction. The sites are presented in the diagram according to their east-western location, with the westernmost site to the left and the easternmost site to the right. Note! Since the tool for measuring the active layer thickness was only 1 m, this was the maximum thickness possible to measure. The three sites with a recorded ALT of 1 m may therefore have a much thicker active layer.

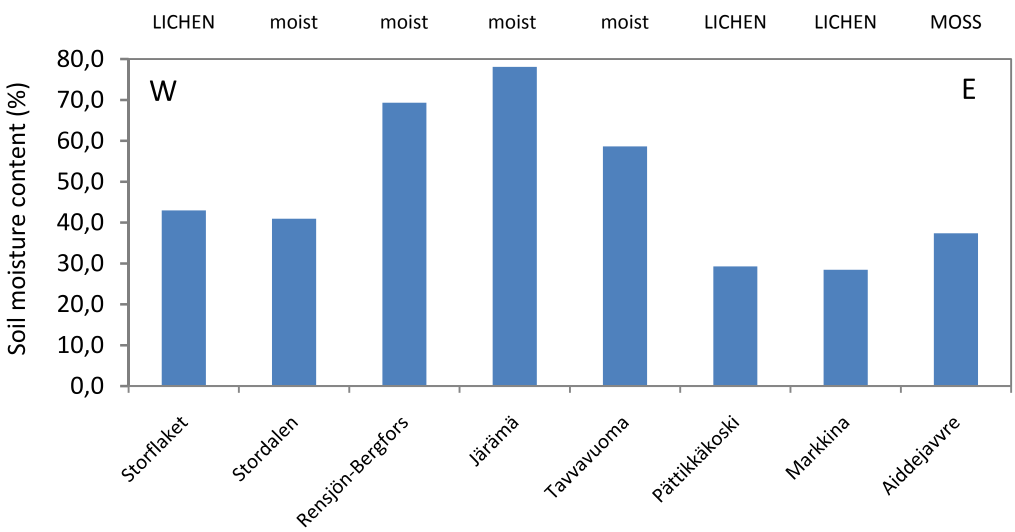


Figure 6.2 Soil moisture content (SMC) and vegetation types in the hummock areas are compared for a selection of sites in the east-western direction. Vegetation types written in capitals indicate that the site is hummock dominated. The sites are presented in the diagram according to their east-western location, with the westernmost site to the left and the easternmost site to the right. Note! The SMC values for Rensjön-Bergfors and Järämä may be overestimated due to heavy rains during the days of measurements.

(*a*)

(*b*)

Figure 6.3 (***a***) Moist hummock vegetation (site nr 2). The hummocks are low and covered with *Sphagnum* mosses, *Rubus chamaemorus* (Cloudberries) and dwarf shrubs. The hummock is surrounded by carpet vegetation. (***b***) High palsa in Aiddejavvre (site nr 4) Bottom layer on top of the palsa consists of lichens and barren peat. On the slopes the field layer is dominated by *Rubus chamaemorus* and dwarf shrubs such as *Empetrum hermaphroditum* (Mountain crowberry). Cracks in the surface peat layer are visible.

Table VII in Annex II lists the climate suitability of all sites. A tendency of wet site vegetation being more predominant at sites with lower climate suitability can be discerned (Figure 6.4*a*). This is in agreement with the assumption of vegetational development on degrading palsas following a wetness gradient: from dry palsas to moist hummocks, carpet and tall graminoid vegetation. However due to a low number of sample sites, detailed features from the results may be unreliable and relations between climate suitability and vegetational patterns should be regarded merely as general trends. When studying differences in hummock vegetation types, i.e. the predominating vegetation in hummock areas (regardless whether the site is hummock or wet dominated), there is a clear trend of hummock vegetation changing from moss to lichen to moist hummock with decreasing climate suitability (Figure 6.4*b*), in line with the theory of lichen hummocks being favoured by early and rapid snow melt-off in spring (Malmer *et al.*, 2005).

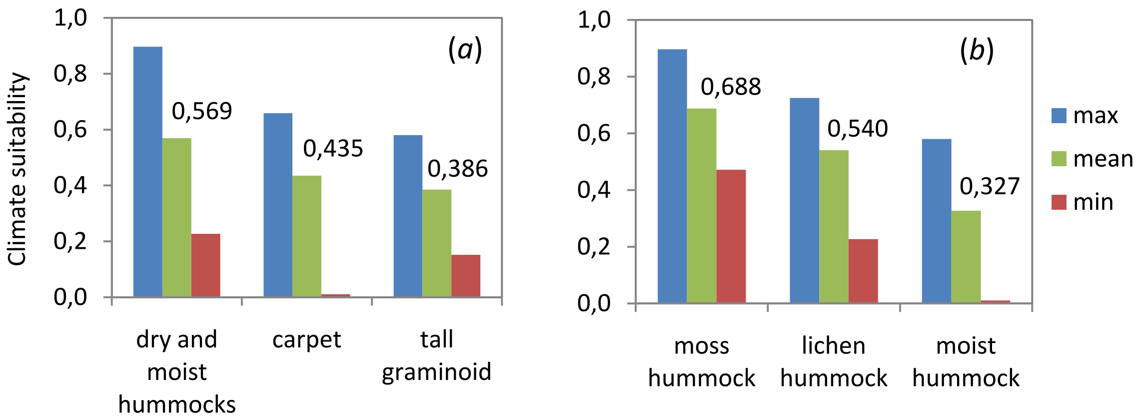


Figure 6.4 Relations between climate suitability and vegetation types in the visited sites. (***a***) presents the *dominating* vegetation types and (***b***) presents the different *hummock* vegetation types, i.e. the predominating vegetation type in the hummock areas, regardless of whether the site was hummock- or wet dominated. *max* (blue bars) represent the site with the highest climate suitability in the given vegetation category, *min* (red bars) represent the site with the lowest climate suitability, correspondingly. *mean* (green bars) is the calculated average value (displayed in the diagram) of climate suitability for the sites of a given vegetation type.

6.2 Climate induced changes in vegetation and GHG fluxes

To illustrate how the areal distribution of the four vegetation types changes between 1990 and 2080 the results are presented in Figure 6.5*a-g*. Results are presented for both minimum and maximum change scenarios. Minimum scenario means temperature and precipitation are increased by the lower rate (0.35°C and 1.5% per decade respectively), maximum scenario is that of the higher rate (0.4°C and 2% increase per decade respectively), see Table 6.2. It is clear that the hummock vegetation (including moist hummock vegetation) decreases rapidly to the benefit of tall graminoids, which is increasing to the same (areal) extent. Half of the area covered with hummock vegetation has disappeared within 30 years, and almost completely vanished after 60 years. When studying the change in areal distribution of the HMC class, the major decrease in areas suitable for palsas are located to the south-western and northernmost parts, while hummock mire pixels located centrally in the study area are the last ones to disappear.

The former dry and moist hummock areas are initially replaced by carpet vegetation in the model, but within 60 years carpet vegetation has decreased from over 60% to less than 15% areal coverage for the benefit of tall graminoid vegetation. The results from the modelling of the climate induced vegetational changes are also presented in Table VIII-IX, Annex II.

The effects on GHG fluxes are illustrated in Figure 6.6*a-e*. The flux values are calculated based on the areal coverage of each vegetation type. In Figure 6.6*a* the GHG fluxes are summed up for all four vegetation types within the study area (CO_2 and CH_4 separately), corresponding to the total areal coverage of 552020 ha (the area *originally* classified as hummock mire complex).

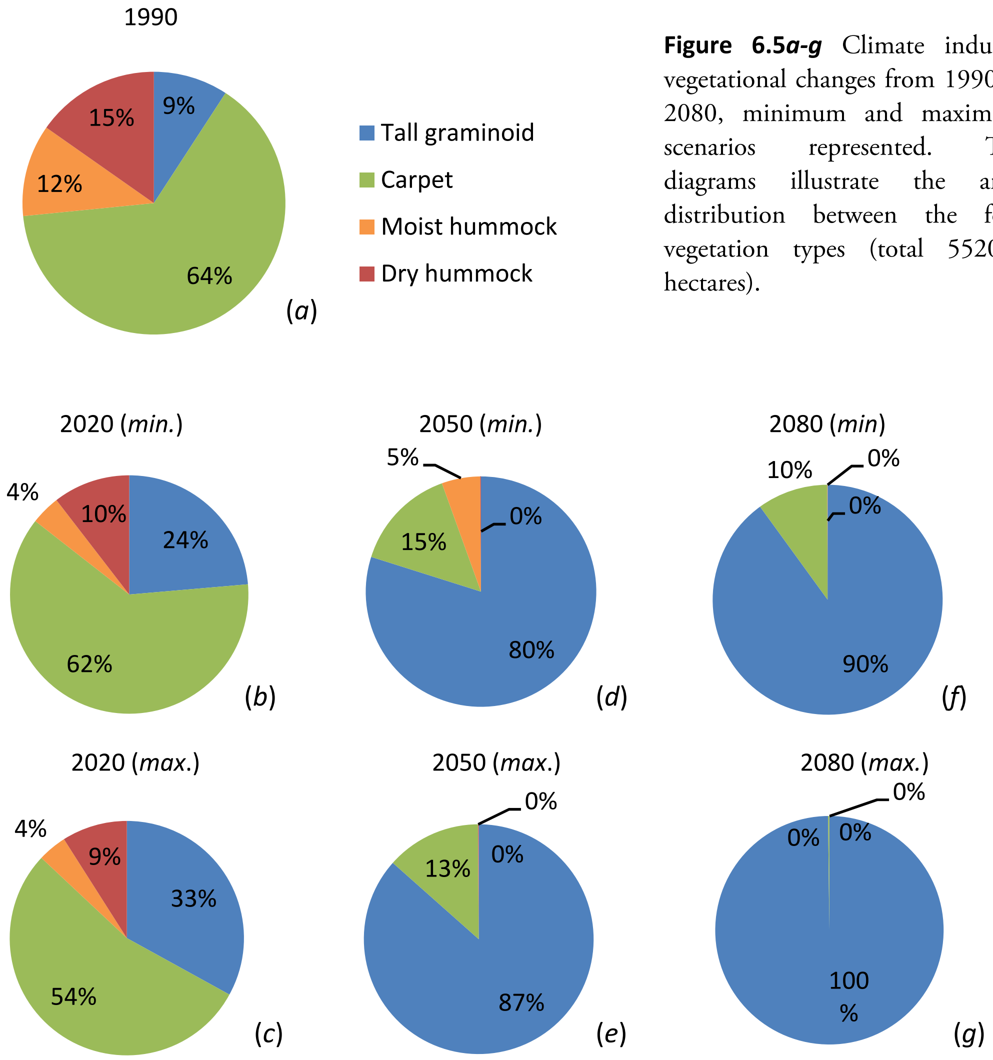


Figure 6.5*a-g* Climate induced vegetational changes from 1990 to 2080, minimum and maximum scenarios represented. The diagrams illustrate the areal distribution between the four vegetation types (total 552020 hectares).

Comparing the modelled GHG fluxes for each of the four vegetation types it is evident that tall graminoids make up for most of both the methane release and the carbon dioxide uptake, even at an early stage when tall graminoids only constitutes between 25-33% of the total area (Figure 7.5*b-c*). Figure 7.6*a* also indicates that by 2050 the mass of released CH_4-C almost equals the mass of sequestered CO_2-C. However, since the global warming potential of methane is more than 20 times larger that of carbon dioxide on a 100 years horizon (more than 50 times on a 20 years horizon), the net effect is a positive radiative forcing significantly stronger than that of today.

At a low estimate the total net flux of methane from former hummock areas is projected to be a release of 64 (146) kilo-tonnes CH_4-C yr^{-1} in 2020 (2050), equivalent to 1784 (4094) kilo-tonnes CO_2 yr^{-1}. This is an increase by more than 50 (250) percent from 1990, corresponding to an average yearly *emission* increase of 1.4 (3.2) kg CH_4-C ha^{-1}. Accordingly, the change in CO_2 fluxes is an increased net *uptake* from 120 kilo-tonnes CO_2 yr^{-1} in 1990 to 150 (183) kilo-tonnes CO_2 yr^{-1} in 2020 (2050), equivalent to an average yearly increase of 1.8 (1.9) kg CO_2-C ha^{-1}.

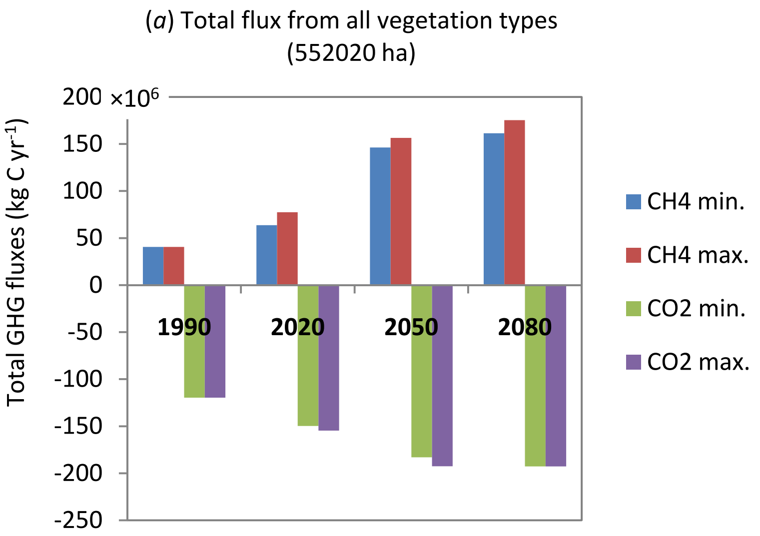
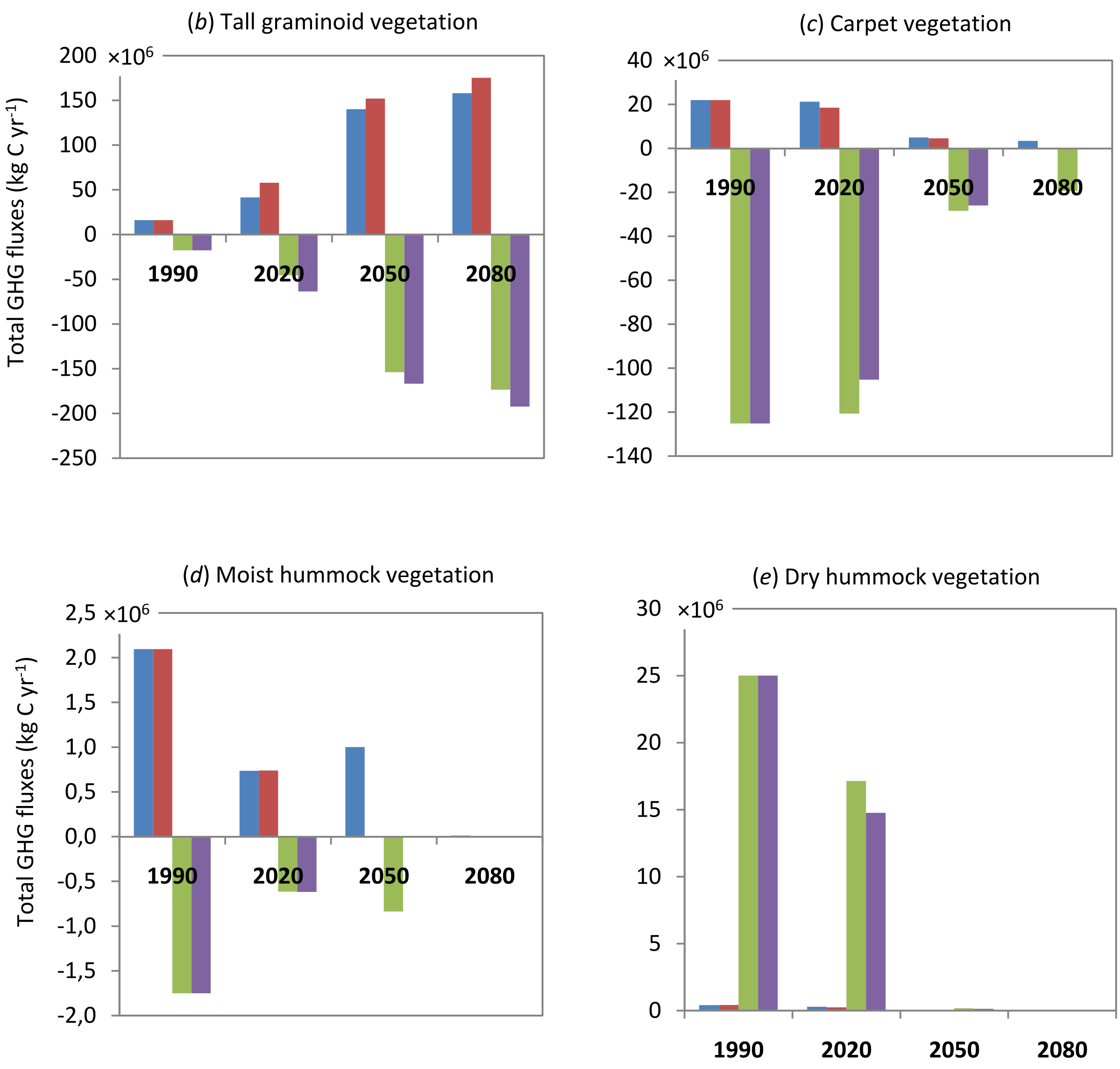


Figure 6.6*a-e* Yearly fluxes of CH_4 and CO_2 for (***a***) all vegetation types summed up and (***b-e***) each vegetation type individually. Minimum and maximum scenarios are presented. The flux values are calculated for the area originally categorized as hummock mire complex, with a total areal coverage of 552020 hectares. *Note the scale differences on the vertical axis.*



7 DISCUSSION

7.1 FIELD OBSERVATIONS AND VEGETATION CLASSIFICATION

The major finding is that surface structures and associated vegetational patterns similar to what has been observed on the Stordalen mire could also be observed in the visited palsa mires. Where the degradation of permafrost was far advanced with only low palsas or remnants of former palsas left (barren peat ridges, circular ponds *etc*.), the vegetation was generally wet-dominated by either carpet vegetation or tall graminoids, or both. Also, at these sites, patches of tall shrubs often occurred both in depressions and on top of the remnant palsas, indicating a relatively thick snow cover during winter. Based on these observations the hypothesis is considered to be confirmed, i.e. the vegetational changes due to degradation of permafrost on the Stordalen mire *is* a general phenomena, in the study area.

The measurements of ALT revealed that where degradation of palsas have proceeded far enough to influence the hummock vegetation, the active layer is significantly thicker than in other areas. Four of five sites with predominating moist hummock vegetation in the hummock areas coincide with the lowest palsa height (< 1m) and the thickest active layer: 90 cm or more. In all the other sites the active layer was no thicker than 62 cm. According to Seppälä (1982b), an active layer thicker than 70 cm may be critical for the palsa development. If the uppermost layer of unfrozen peat is too thick at the end of the thawing season the frost may not be able to penetrate down to the permafrost table during the next winter. Instead the thawing of the frozen core will continue during the following years, finally leading to a collapse of the palsa. No signs of new formation of palsas were observed, in line with the theory of a general imbalance between degradation and new formation of palsas in the region (Luoto and Seppälä, 2003; Zuidhoff, 2002; Sollid and Sørbel, 1998 *etc*.).

The tendency of palsa mires in the westernmost parts being more subjected to thawing and degradation than those located further north east may indicate that the distribution of palsa mires is shifting towards the northeast where climate is more continental. These observations are in accordance with results from other studies: Åkerman and Johansson (2008) reported that from 1978 to 2006 average thawing depths had increased at nine out of nine studied sites located in the Torneträsk region (the region surrounding Stordalen), while Seppälä (2003) reports no unusual development of active layer thickness in northeastern Finland. Instead, new formation of permafrost has been observed in peat hummocks (pounus) in Finnish Lapland (Seppälä, 1998). However, since the eastern-most of the visited sites are located in the centre part of the study area, this trend may not extend further east. Possibly the degradation of palsa mires may be larger further north-east as the climate becomes more affected by the proximity to the sea.

7.2 MODELLING CLIMATE AND CLIMATE CHANGES

In previous studies palsa occurrence in northern Fennoscandia have been modelled based on several climate parameters such as mean annual air temperature, mean annual precipitation, winter precipitation, summer precipitation, number of frost days, continentality etc. (Parvainen and Luoto, 2007; Luoto *et al*., 2004a, Fronzek *et al*. 2006). Parvainen and Luoto (2007) also included spatial variables to account for the geographical location. In the present modelling only two climate parameters were used: MAAP and MAAT. Optimally more climate parameters should be included in the modelling, especially seasonal precipitation, since snow cover has proven to be a crucial factor for determining the presence or absence of permafrost (Seppälä, 1982a, 1986; Johansson M. e*t al.*, 2006). However, the spatial climate data (i.e. climate maps) available from SMHI, DNMI and FMI differed significantly in format, quality and type of information presented by the maps. For example, only low resolution polygon vector maps of mean annual air temperature and mean annual precipitation were available from SMHI at the time, while DNMI provided raster maps with much higher resolution of both annual and monthly mean values. Hence it would have been very difficult to produce homogenized maps of winter and summer precipitation, covering the whole regions with an acceptable accuracy.

The differences in quality of the climate maps derived from SMHI, DNMI and FMI is also the single largest uncertainty factor in the modelling procedure. The climate maps produced by SMHI had the poorest quality in matter of spatial and physical resolution. On the other hand, the climate conformity over both the Swedish-Finnish and Swedish-Norwegian border was relatively good, while there were large discrepancies between the Finnish and Norwegian climate maps in the border regions of these two countries. The climate maps from FMI were originally composed by a grid of vector points located at a regular distance of 10 km from each other. These points did not represent climate stations but were rather generated from a spline interpolated raster map by FMI. In order to use the FMI climate data in the current modelling process it had to be re-rasterized, again using spline interpolation. For every processing step the uncertainty of the data accuracy becomes higher, lowering the quality. The effect of the double interpolations of the FMI climate data is a smothered appearance, where local variations are erased. All these deficiencies stress the importance and need for integrated (spatial) climate information covering the whole region, especially since the region is subject to several climate-related studies and is expected to experience significant environmental changes with global warming.

7.3 MODELLING VEGETATIONAL CHANGES

One of the major strengths in the modelling of vegetational changes was the high resolution (1ha) land cover map produced by NORUT. In previous modelling of presence/absence of palsas in relation to climate the spatial resolution has been much lower, with a grid size ranging from 1 km2 (Luoto and Seppälä, 2002) to 10’×10’ (ca 123 km^2)(Luoto et al., 2004a; Fronzek *et al.*, 2006) or even 30’×30 km^2 (Parvainen and Luoto, 2007). The purposes of these studies have often been to investigate the relation between presence/absence of palsas and various physical and environmental parameters, where a higher spatial resolution may not necessarily be profitable, although Fronzek *et al.* (2006) point out that a higher spatial resolution could reduce the uncertainty in the modelling of palsa distribution.

For the purpose of the current study, the spatial resolution of the land cover map is essential. In order to quantify potential changes in GHG fluxes associated with vegetational patterns in degrading palsas, it is advantageous if the spatial resolution is close to the spatial extent of a single palsa feature (or other homogeneous unit), otherwise it is necessary to estimate the percentage coverage of palsa features within one single pixel. In the land cover map by NORUT a pixel belonging to the *hummock mire complex* (HMC) class is assumed to be 100% covered by one vegetation type only; dry hummock, moist hummock, carpet or tall graminoids, depending on the climate suitability. This is an unrealistic assumption for individual pixels, since palsa mires are typically a mosaic of several micro habitats, often smaller than that of the pixel size. Also, palsa features do not follow the grid shaped boundaries of individual pixels but may extend across the edges of a pixel. Hence pixels *not* belonging to the HMC class may well contain a minor part of palsa features, but these are not incorporated in the modelling. However, on a large scale where thousands of pixels are incorporated, this type of bias becomes less of a problem since the inaccuracies within individual pixels tend to balance each other.

Possibly, the assumption of only one vegetation type occurring within every pixel may still result in an overestimated areal coverage of dry and moist hummocks. On the other hand, when applying the climate suitability (computed from 1961-1990 normal reference values) to the land cover map, a large portion (64%) of pixels originally belonging to the hummock mire complex class was re-classified to carpet vegetation. Thus, assuming that on average only 27% of a HMC pixel is covered by hummock vegetation and remaining 73% of the pixel is covered by either carpet or tall graminoid vegetation (see Figure 6.5*a*), the total areal coverage of hummock vegetation would eventually not be overestimated.

The role of climate suitability is important. The reason for incorporating climate suitability in the model was the need for some sort of measurement or index describing the climate sensitivity of the vegetation types, in order to describe the relation between climate and vegetational changes analytically. However, setting climate suitability thresholds for each of the vegetation types is problematic since there are no well-defined limits, but one value of climate suitability may correspond to more than one vegetation type. The climate suitability must therefore be considered an indicator of which vegetation types to expect rather than a numerical synonym. The climate suitability value can still be useful in this sense, but the threshold values of the vegetation types should be confirmed through more extensive studies, for example by expanding the number of visited sites and number of parameters influencing the climate suitability, such as seasonal precipitation and elevation. Another aspect of the climate suitability is the relative explanatory level of the included parameters. The possibility of applying weighted parameters in the climate suitability should be investigated in order to account for differences in the relative importance of the included parameters. This would for example enable winter precipitation (*i.e.* snow cover) to have a larger influence than annual precipitation on the modelled distribution of palsas.

Together with the climate data, long term projections are a major source of uncertainty in the model. The model projections of 30, 60, and 90 years from 1990 are static and presume equilibrium between climate and vegetation. This is not very likely since it takes time for vegetation and ecosystems to adapt to new conditions. Besides uncertainties concerning the change in temperature and precipitation, there are also large uncertainties in the vegetational development. The relation between climate, palsa degradation and vegetation is based on observations of the past and the current state. This means that the model rest on the assumption that the vegetational succession in the next thirty years will follow the same pattern from the last thirty years. This is a justified assumption when it comes to the first stages of palsa degradation. However, we know little yet of how the former hummock areas, now wet areas with carpet or tall graminoid vegetation will develop under continued warming and increased precipitation. Could wet areas turn into smaller lakes or open water wetlands, or is there a possibility of the wetter areas drying up as hydrological and climatological conditions changes (Smith *et al.* 2005)? To what extent will tall graminoid vegetation develop into carpet vegetation as the floating patches of *Sphagnum* mosses expand? To answer these question more research in the area is demanded.

7.4 Potential changes in vegetation and GHG fluxes

The modelling results project major vegetational changes in degrading palsa mires within the next 30-60 years, with a rapid loss of hummock vegetation areas to the benefit of carpet and tall graminoid vegetation. This is in line with the study by Fronzek *et al.* (2006) where the climate sensitivity of palsa mires in northern Fennoscandia was modelled. Their results showed a decrease of areas suitable for palsas by more than 50% with 1°C MAAT increase, and a total disappearance with a temperature increase of 4°C. A MAAP increase by 10-20% lead a reduction of the area suitable for palsas by ca 30-50% respectively. Fronzek *et al.* (2006) did not investigate the effects of temperature and precipitation changes combined.

The observed decrease in areas suitable for palsas in mainly the south-western and northernmost parts is also in accordance with the study by Fronzek *et al.* (2006), where modelled climate induced changes in palsa distribution indicated that palsas are least vulnerable to climate changes in the central parts of northern Fennoscandia.

The potential effect of these vegetational changes on CO_2 fluxes is a relatively large increase in carbon sequestration by carpet and tall graminoid vegetation. However this is from a radiative forcing perspective not enough to compensate for the considerable increase in methane emission from the expanding tall graminoid vegetation. The largest changes in vegetation and GHG fluxes are projected to occur between 2020 and 2050, when hummock areas almost completely disappear and carpet vegetation to a major extent is replaced by tall graminoids. The associated change in CH_4-release to the atmosphere from 1990 to 2020 (2050) corresponds to a yearly increase of 1.4 (3.2) kg CO_2 ha^{-1} yr^{-1}. The projected increase of methane emissions from degrading palsas can be compared to statistics of antropogenic emissions: by 2020 thawing palsa mires in the studied area may contribute with 64 kilo-tonnes CH_4-C yr^{-1} to the atmosphere, equivalent to 1784 kilo-tonnes CO_2 yr^{-1}. This exceeds the amount of CH_4 released from waste management in Sweden 2006, and corresponds to more than 50% of the CH_4 released from the Swedish agricultural sector for the same year (Swedish Environmental Protection Agency, 2008).

The occurrence of tall graminoids alone explains most of the changes in GHG fluxes, mainly since tall graminoids differ significantly from the other vegetation types in both CO_2 and CH_4 flux rates. Therefore the differentiation between carpet and tall graminoid vegetation in terms of climate suitability plays a major role in the timing of vegetational changes. As briefly discussed in the previous section, there are uncertainties concerning the vegetational succession as climate conditions changes. Based on the results from field observations and the calculated climate suitability of the sites, carpet vegetation is assumed to precede tall graminoids in the vegetational succession of degrading palsas. Studies from the Stordalen mire affirm this theory: interpretations of CIR images of the mire showed a decrease in dry and moist hummock areas by 0.53 ha during the last thirty years, from 9.20 ha in 1970 to 8.67 ha in 2000. During this period areas dominated by tall graminoids increased by 0.62 ha, almost twice the increase of carpet vegetation (0.35 ha), with the expansion of tall graminoids mainly located to areas previously dominated by carpet vegetation (Malmer *et al.*, 2005).

However, in the present study the difference between climate suitability of carpet vegetation and tall graminoid vegetation was small, and at several locations (especially in the north-eastern parts with the highest climate suitability) tall graminoid vegetation was recorded together with high palsas of mature or initially degrading stage, while carpet vegetation was lacking. This indicates that tall graminoid vegetation might not necessarily represent the last stage of degradation but rather an expansion of the water pools often surrounding collapsing palsas. Carpet vegetation on the other hand was frequently recorded in mires with peat plateaus (generally lower than palsas) or low palsa remnants. The climate suitability threshold for tall graminoids may thus be under-estimated. If so, by 2020 a larger portion of the area *un*suitable for palsas would be covered by tall graminoids, on the expense of carpet vegetation. As a consequence the major change in vegetation cover and GHG fluxes may occur already between 1990 and 2020. Still, on a 60 years horizon, tall graminoids is projected to have replaced most of the former hummock and carpet vegetation.

By 2080 though, climatic changes may have altered the environmental conditions enough to allow for a re-growth of carpet vegetation or expansion of tall shrubs and forest vegetation, a scenario not investigated in this study.

Finally, one should keep in mind that this study has focused on how vegetational patterns affect the carbon fluxes in terms of CO_2 and CH_4. There are other important factors controlling these flux rates including the direct impact of a changing climate *i.e.* changing air and soil temperatures as well as available soil moisture through changing precipitation patterns. For example in a future climate soil temperatures may be higher than that of today, which most likely will result in increasing decomposition rates that may release more of both CO_2 and CH_4 to the atmosphere. Further studies should focus on combining these different components of change by superimposing the effects of direct climate onto the changes in the vegetational patterns documented here.

8 CONCLUSIONS

Field observations presented in this study show that the changes in surface structures and vegetational patterns associated with degrading permafrost on Stordalen mire, northern Sweden represent general phenomena within subarctic mires in the studied region. However uncertainties remain concerning the expansion of tall graminoids vs. carpet vegetation. This study shows that GHG flux measurements from Stordalen (Bäckstrand, 2008) are thus considered to be applicable at a larger scale and may well be used for up-scaling GHG flux measurements from Stordalen mire to other palsa mires in northern Fennoscandia.

Observations from the visited sites revealed differences in the stage of palsa degradation that may be linked to their location on an east-western gradient. Generally, palsa mires in the western parts of the studied area were subjected to substantial thawing, with thicker active layers and a larger cover of wet areas dominated by carpet and tall graminoid vegetation, while the degradation of palsas located further east (i.e. in the central parts of the study area) are not as far advanced, indicating that palsa mires located centrally with a more continental climate in the study area are less vulnerable to climate changes.

The modelling of climatic and vegetational changes shows that palsas and peat plateaus is projected to experience a rapid decrease in areal coverage, resulting in almost a 100% loss of dry and moist hummock areas (corresponding to 1470 km^2) within 50-60 years. The associated change in GHG fluxes is increased CO_2 sequestration *and* increased methane emissions, mainly due to the expansion of tall graminoids. Since methane has a much higher global warming potential than carbon dioxide, the net effect is a considerably stronger positive radiative forcing, *i.e.* more GHG is being released to the atmosphere than what is taken up by the ecosystem, even within a relatively short time period.

For future work, the relationship between the different vegetation types and climate conditions need to be further investigated, in order to support the use of climate suitability thresholds when modelling climate induced vegetational changes. Also, better understanding of long term vegetational succession in wet areas is of importance for estimating potential changes in GHG fluxes with future climatic changes. Integrated and detailed climate data, including parameters such as snow cover and wind, covering the whole region of northern Europe would also be of great importance for future climate-related modelling.

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ANNEX I: SITE DESCRIPTIONS AND VEGETATION CLASSIFICATION

Table I. A summary of the site characteristics based on previous studies.

Nr	Site	Site characteristics
1	**Rensjön-Bergfors**	Palsa mire complex covering ca 113 ha, according to the county administration board in Norrbotten, Sweden. Located in the nature reserve and Natura 2000 area of Rautas mountain primeval forest, municipality of Kiruna. Not included in the mire protection plan for Norrbotten (County Administration Board of Norrbotten, 2008).
2	**Järämä**	Large area with several smaller (< 50 ha) palsa mire complex, located in the large Nature reserve of Torneträsk-Soppero, Sweden. Included in the Natura 2000-program, but not included in the mire protection plan of Norrbotten (County Administration Board of Norrbotten, 2008)
3	**Tavvavuoma**	Several large palsa mires located in the valley between two lower mountains (Palkesvare and Tavvaskaite), 10 km north-west of Pulsujärvi, Sweden. Situated north of the Torneträsk-Soppero Nature reserve and covered by the Ramsar convention, Natura 2000 and the mire protection plan of Norrbotten. Many well developed palsas with a height of 6-7 m. Together with thermokarst ponds the area is a mosaic of different environments, rich in both plant and animal species, birds in particular. (Swedish Environment Protection Board, 2007)
4	**Aiddejavvre**	The mire covers ca 15 km^2 and is situated about 30 km south of Kautokeino, Norway, extending on both sides of the federal highway 93. The area has a typical continental climate with extreme winter temperatures and very little precipitation. The mire is a rich complex of several different mire types, but is dominated by palsas and peat plateaus. It is a valuable area for both its complexity of mire types and its rich birdlife (County Governor of Finnmark, 1980; Strann and Nilsen, 1996)
5,6	**Stuorajavvre 1 + 2**	A large mire complex (>100 km^2) in the area of lake Stuorajávri, northwest of Kautokeino, Norway. The area has been studied for a long time for its valuable mire complex with large palsas, plateaus and rich birdlife. It has been suggested to be part of a national mire protection plan in Norway. (County Governor of Finnmark, 1980; *Bjerke et al.*, 2005; Strann and Nilsen, 1996)
7	**Markkina**	Palsas of 1-2 m height (Seppälä, 1982b)
8	**Pättikkäkoski**	Palsas of 1-2 m height (Seppälä, 1982b)
9,10	**Saukkokoski S + N**	Palsas of 3-6 m height (Seppälä, 1982b)
11	**Keinovuopio**	Area with low mountains (up to 750 m), birch forest and heath vegetation. Palsa area (located at 450 m ASL) is waterlogged and acidic with a 15-110 cm thick peat layer. Observed palsas are dome-shaped or plateau-like, some of the palsas forming complex 30-70 m in diameter and a height of approximately 3 m (Zuidhoff, 2003)
12	**Peera**	Palsas of 3-7 m height (Seppälä, 1982b)
13	**Tromsø**	No records of observed palsas found
14	**Stordalen, Storflaket**	Birch forest located near Torneträsk, in the Stordalen Nature Reserve, also protected by Natura 2000. Reference area for climate research, where large palsas were to be found in the past. Today large areas have experienced a degradation of palsas, but palsa remnants and peat plateaus can be seen. The Stordalen mire is not included in the Swedish mire protection plan. (County Administration Board of Norrbotten, 2008)

Table II. Description of vegetation classes, comparing Malmer *et al.* (2005) with NORUT land cover map (Johansen, 2008, personal communication)

Vegetation types by Malmer *et al.*(2005)		Land cover classes by NORUT (2006)	
Moss and lichen hummock vegetation	Rich occurrence of dwarf shrubs, hummock bryophytes and lichens (the hummock vegetation types). A gradient from lichen-dominated to moss-dominated vegetation types in the bottom layer. Moss hummock vegetation dominated by hummock *Bryatae* and *Sphagnum* sect. *Acutifolia,* lichen hummock vegetation dominated by lichens and hummock *Hepaticae*. *Rubus chamaemorus* may also be found.	**Hummock mire complex (12)**	The hummocks mires are normally found in the upper part in the hummock - mud-bottom gradient. The peat layer is normally thin, often overlaying stony gravel and boulders. *Betula nana*, *Empetrum hermaphroditum*, *Ledum palustre* and *Rubus chamaemorus* are dominating species. Carpets of *Sphagnum* constitute the ground layer. Several variants of hummock mires can be recorded.
Moist hummock vegetation	Less dwarf shrubs than in the dryer hummock sites, bottom layer of *Sphagnum*. Intermediate between hummock and wet site vegetation and therefore less distinct.		
Carpet vegetation	Dense bottom of *S. balticum* and carpet *Bryatae* while the low-grown graminoids *Eriphorium vaginatrum* and *Carex rotundata* form a field layer much sparser than that of the hummock vegetation.	**Lawn and carpet mire complex (13)**	A broad complex of mostly base-poor and some neutral mire community types dominated by grasses, sedges and few heather species. A uniform *Sphagnum* moss carpet normally constitutes most of the ground layer. The peat layer is normally thick.
Tall graminoid vegetation	Vegetation characterized by *Carex rostrata* and *Eriphorum angustifolium*, often forming dense stands in shallow water with floating moss mats. Particularly abundant along the shore of the lakes.	**Mud-bottom fens and sedge marches (15/16)**	Mires characterized by a high level of the water table through the growing season. The vegetation cover consists of a low number grass and sedges demanding wet growing conditions. A mosaic of lawns, moss carpets and open waters is characteristic for these mire types. Sedge marches are found around lakes and along rivers.
Tall shrub vegetation	Tall-grown stands of *Betula nana* form a physionomically distinct component in the vegetation. They occur in hummocks, particularly on sloping surfaces and in carpet vegetation.	**Wooded mire complex (14)**	A complex of mostly base-poor to neutral mire types are separated from other mire complexes in possessing a dense shrub layer of *Salix glauca*, *S. lapponum,* and *Betula nana*. A dry variant of this mire complex is comparable to the hummock mire-complex with shrub layer of grey willows. Grasses and sedges dominate the field layer, whereas *Sphagnum* often constitutes the ground layer.

Table III. Observed site characteristics

Nr	Site	Site characteristics
1	**Rensjön - Bergfors**	Large mire with predominantly wet areas. Dryer parts with moist hummocks, rockbed and large boulders. Strands of elevated areas with birch and tall shrubs, a few isolated ponds.
2	**Järämä**	Mire situated in between low hills. Predominantly wet carpet vegetation with low moist hummocks along the edges.
3	**Tavvavuoma**	Large mire complex located in a valley. Pounus with tall shrubs along the edges, a few large collapsed palsas. Surface cracks, bare peat and distinct ridges and pools.
4	**Aiddejavvre**	Two large peat plateaus, separated by open water and dense graminoid vegetation. Large dome-shaped palsas along the edge of the first plateau. Surface cracks and sliding peat blocks. Several large circular thermokarst ponds indicating former palsa occurrence.
5	**Stuorajavvre 1**	Low peat plateau and two large oval-dome shaped palsas. Surface cracks and peat blocks sliding down the edges. Palsas surrounded by pools and dense bush and sedge vegetation. Patches of dense birch stands.
6	**Stuorajavvre 2 (smaller)**	Smaller mire with a peat plateau and a small collapsed palsa. Large cracks in the surface peat and major block erosion, adjacent pools of shallow water. Stands of birch and tall shrubs surrounding the palsa.
7	**Markkina**	Large peat plateau at the foot of a hill. Parts with palsa formations, many of them collapsed with surface cracks, barren peat and thermokarst ponds. Several isolated ponds and wet areas with shallow open water. Strands of moist hummock vegetation and tall shrubs.
8	**Pättikkäkoski**	Two smaller peat plateaus with low palsa remnants and larger ponds. Located relatively close to the Torne River, surrounded by stands of birch forest.
9	**Saukkokoski S**	Small mire at the foot of a hillside. Degraded palsas with barren peat, surface cracks and pools. Wet areas with sedges and sphagnum mosses. Possibly underlain by rockbed since large boulders were found nearby.
10	**Saukkokoski N**	Mire located between hills, near the Torne river, extending on both sides of the road. Low peat plateau with pools and depressions, surrounded by moist areas and birch stands/bush vegetation.
11	**Keinovuopio**	Large peat plateau with only few depressions located between Torne river and a minor watercourse. Homogeneous vegetation on the plateau, with surrounding wet areas dominated by sedges. Nearby another peat plateau and high palsas, seen from distance.
12	**Peera**	Large palsa or small (high) peat plateau situated close to the road. Several small ponds and depressions, large surface cracks and pools along the edges. Wet surroundings with mosses, open water, and dense sedge vegetation. Mire surrounded by birch forest.
13	**Tromsø Camping**	Small site located in a valley. Low hummocks with bare peat. Wet areas with carpet mosses, sedges and tall shrubs. Mire surrounded by low trees and bush vegetation.
14	**Stordalen**	Low moist hummocks with tall shrubs. Wet surroundings, mainly tall graminoids. Difficult to measure active layer thickness due to underlying rockbed.
15	**Storflaket**	Small mire at the foot of the hillside, surrounded by stands of birch and bush vegetation. Peat plateaus on both sides of the road, only a few depressions and pools. Deep cracks and block erosion along the edges. Plateau surrounded by wet areas, composed by mainly tall graminoid vegetation and open water.

Table IV. Results from observations of active layer thickness, soil moisture content and dominating vegetation types. Active layer thickness and soil moisture content are average values of 10-15 sample points per site. Vegetation types written in capitals demark whether the site is hummock- or wet dominated.

Nr	Site	Height of palsa/plateau (m)	Active layer thickness (cm)	Soil moisture (%)	Dominating vegetation type	
					Hummock areas	*Wet areas*
1	**Rensjön-Bergfors**	0.75	100	-	moist	TALL GRAMINOID
2	**Järämä**	0.35	100	-	moist	CARPET
3	**Tavvavuoma**	2.5	57	58.6	moist	TALL GRAMINOID
4	**Aiddejavvre**	3.5	53	37.4	MOSS	tall graminoid
5	**Stuorajavvre**	6	54	36.9	moss	TALL SHRUB
6	**Stuorajavvre (small)**	3	53	39.2	lichen	TALL SHRUB
7	**Markkina**	2.5	61	28.5	LICHEN	CARPET
8	**Pättikkäkoski**	1.5	46	29.3	LICHEN	carpet
9	**Saukkokoski S**	2.5	50	27.8	lichen	CARPET
10	**Saukkokoski N**	2	62	32.3	MOSS	carpet
11	**Keinovuopio**	2	48	34.1	MOSS	carpet
12	**Peera**	3	57	35.5	lichen	TALL GRAMINOID
13	**Tromsö Camping**	0.6	90	68.6	moist	CARPET
14	**Stordalen**	0.5	100	40.9	moist	TALL GRAMINOID
15	**Storflaket**	1.5	55	43.0	LICHEN	tall graminoid

ANNEX II: COMPUTATIONS AND MODELLING

The climate suitability curves were produced by fitting functions to the threshold and optimum values of the MAAP and MAAT curves from Luoto *et al.* (2004), Figure 6.2. The threshold and optimum values used for fitting the functions are listed in Table V below.

Table V. Climate threshold and optimum values for the probability of palsa occurrence (Luoto et al., 2004a)

	MAAP curve		MAAT curve	
Probability of occurence (*P*)	Min. (mm yr^{-1})	Max. (mm yr^{-1})	Min. (°C yr^{-1})	Max. (°C yr^{-1})
Threshold: *P* > 5 %	-	720	-	-0.33
Optimum: *P* > 50 %	-	445	-4.99	-2.87

Two different functions were used to produce the MAAP curve and the MAAT curve. The two functions used in the curve fitting are the same functions used by IDRISI 15.0 (Andes edition) in fuzzy membership computations. The general equation used for fitting the J-shaped MAAP curve is

$$\mu_{prec} = \frac{1}{\left[1+\left(\frac{x-a}{a-b}\right)^2\right]} \qquad (1)$$

Parameter a denotes the point (precipitation in mm yr^{-1}) where climate suitability equals 1 and parameter b is the point (precipitation in mm) where the climate suitability is 0.5. Since the J-shaped curve of precipitation reaches probability of 1 when interpolated, the curve does not need to be rescaled, but the climate suitability is equal to probability values. Therefore b is 445 mm yr^{-1} which is the same point as where the probability of occurrence equals 0.5.

A cosinus function is used to fit the sigmodial curve of MAAT in Figure 5.2*b*:

$$\mu_{temp} = A\cos^2\alpha \qquad (2)$$

with

$$\alpha = \frac{x-c}{c-d}\cdot\frac{\pi}{2} \qquad (3)$$

c is here the point (temperature in °C) where climate suitability equals 1 (i.e. the peak of the curve), d is the point (temperature in °C) where climate suitability equals zero. A is a scaling factor between the amplitudes of the probability and suitability curves. The climate suitability curve is therefore rather described by

$$\mu_{temp}^{*} = \cos^2\alpha \tag{4}$$

The parameters A, a, b, c and d were calculated using the MATLAB 7.5.0 curve-fitting tool. Results are presented in Table VI.

Table VI. Parameter values computed to fit eq. 1 and 2 to the MAAP and MAAT curves produced by Luoto *et al.* (2004*a*)

MAAP curve		MAAT curve		
a (mm)	*b* (mm)	*c* (°C)	*d* (°C)	*A*
363.1	445.0	-3.93	0.515	0.577

From the two climate suitability curves, a total suitability value (fuzzy membership value) is given for every site, describing the relative climate suitability as a function of both temperature and precipitation. The total climate suitability is calculated as

$$\mu_{tot} = \mu_{precip} \cdot \mu_{temp}^{*} \tag{5}$$

Table VII presents the total climate suitability for all sites computed for the estimated MAAT and MAAP values.

Table VII. Total climate suitability computed for all sites

Nr	Site	Estimated MAAT (°C)	Estimated MAAP (mm yr^{-1})	Climate suitability
1	**Rensjön-Bergfors**	-1.7	420	0.335
2	**Järämä**	-3.4	433	0.558
3	**Tavvavuoma**	-3.8	433	0.580
4	**Aiddejavvre**	-3.0	366	0.897
5	**Stuorajavvre**	-3.2	408	0.720
6	**Stuorajavvre (small)**	-3.2	408	0.725
7	**Markkina**	-2.3	415	0.512
8	**Pättikkäkoski**	-2.8	410	0.645
9	**Saukkokoski S**	-2.9	410	0.659
10	**Saukkokoski N**	-2.9	410	0.662
11	**Keinovuopio**	-2.7	434	0.472
12	**Peera**	-2.7	434	0.474
13	**Tromsö Camping**	3.2	1000	0.011
14	**Stordalen**	-0.6	304	0.152
15	**Storflaket**	-0.9	304	0.227

Table VIII. Computed changes in areal coverage from 1990 to 2080, both minimum and maximum increase rates represented. Since each pixel is equals one hectare, the *total* areal coverage of all vegetation types is equivalent to the total number of pixels being modelled (552020 pixels).

TOTAL areal coverage (ha)	1990	2020	2050	2080
Dry hummock (*min.*)	84195	57714	607	0
Dry hummock (*max.*)	84195	49704	461	0
Moist hummock (*min.*)	62536	21932	29879	338
Moist hummock (*max.*)	62536	22065	148	0
Carpet (*min.*)	354643	341877	80588	54903
Carpet (*max.*)	354643	298077	73568	982
Tall graminoid (*min.*)	50646	130495	440945	496779
Tall graminoid (*max.*)	50646	182173	477843	551037

Table IX. Computed changes in GHG fluxes due to the climate induced vegetational changes, both minimum and maximum scenarios represented. The flux values are calculated as a total of fluxes from all four vegetation types within the 552020 ha area (negative sign indicates a net uptake).

TOTAL GHG fluxes (*tonnes/yr*)	1990	2020	2050	2080
Total flux CO_2-C (*min.*)	-119610	-149698	-182994	-192766
Total flux CO_2-C (*max.*)	-119610	-154655	-192604	-192659
Total flux CH_4-C (*min.*)	40609	63717	146221	161391
Total flux CH_4-C (*max.*)	40609	77399	156523	175291

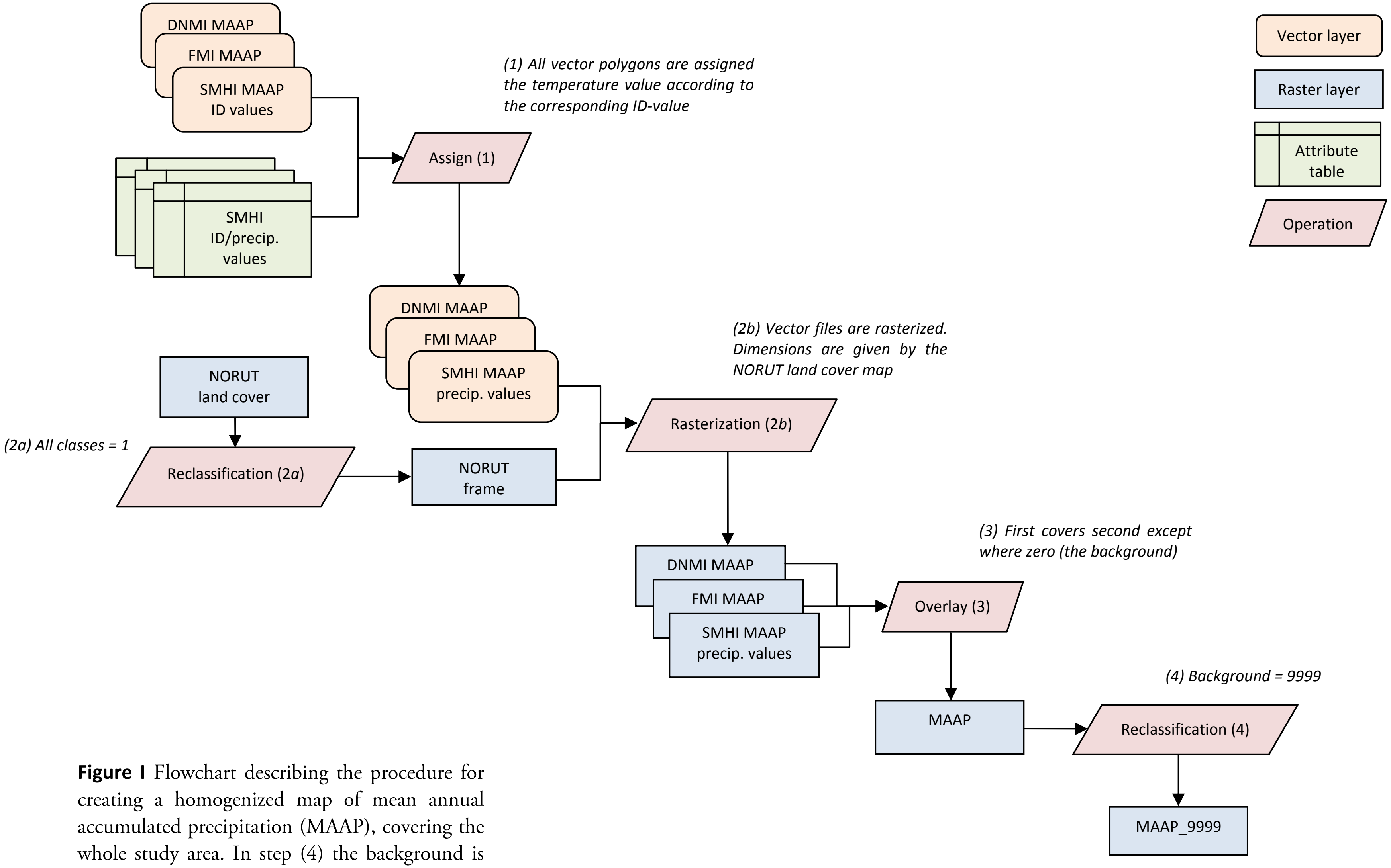

Figure I Flowchart describing the procedure for creating a homogenized map of mean annual accumulated precipitation (MAAP), covering the whole study area. In step (4) the background is given unrealistic high values in order to avoid a climate suitability >0

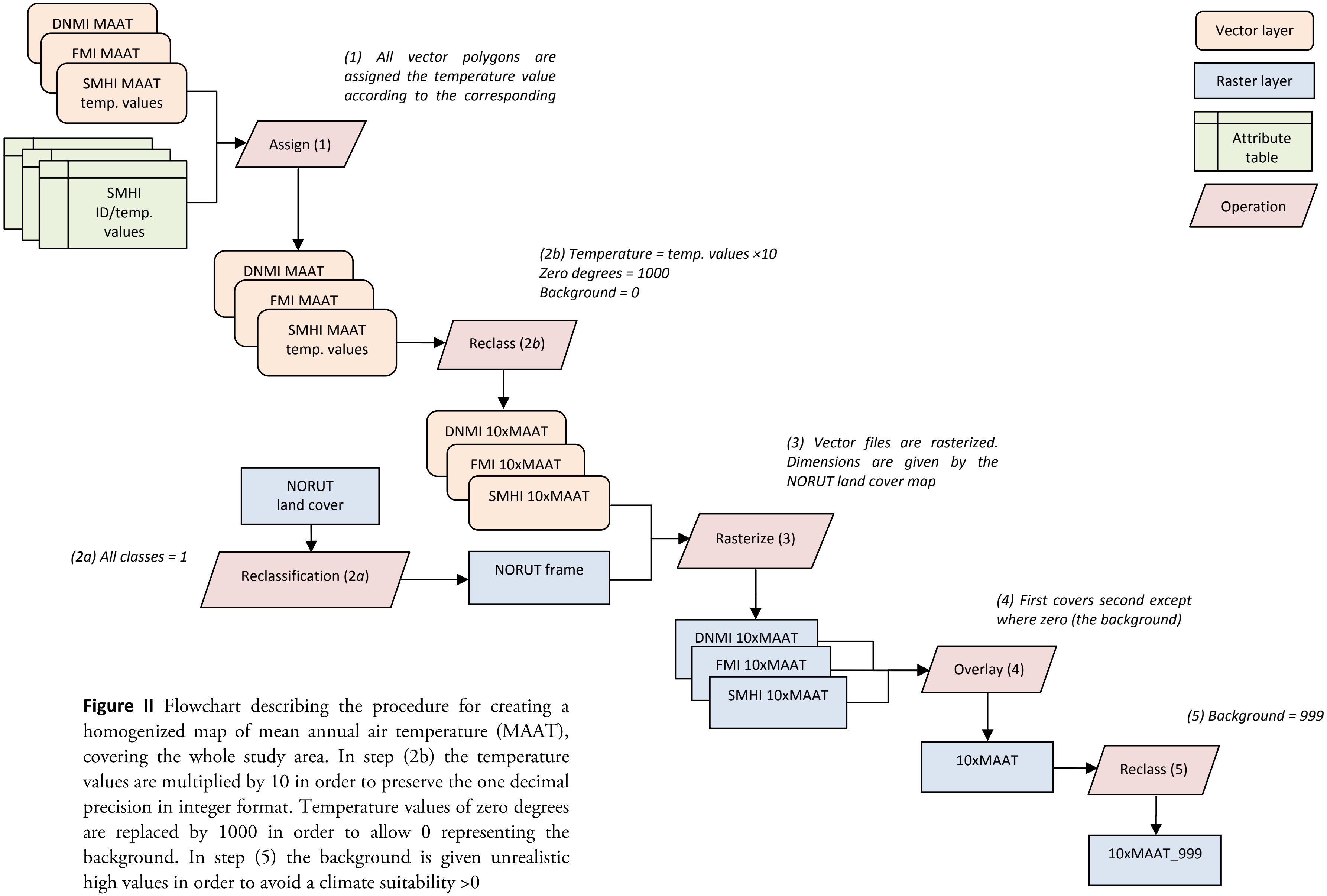

Figure II Flowchart describing the procedure for creating a homogenized map of mean annual air temperature (MAAT), covering the whole study area. In step (2b) the temperature values are multiplied by 10 in order to preserve the one decimal precision in integer format. Temperature values of zero degrees are replaced by 1000 in order to allow 0 representing the background. In step (5) the background is given unrealistic high values in order to avoid a climate suitability >0

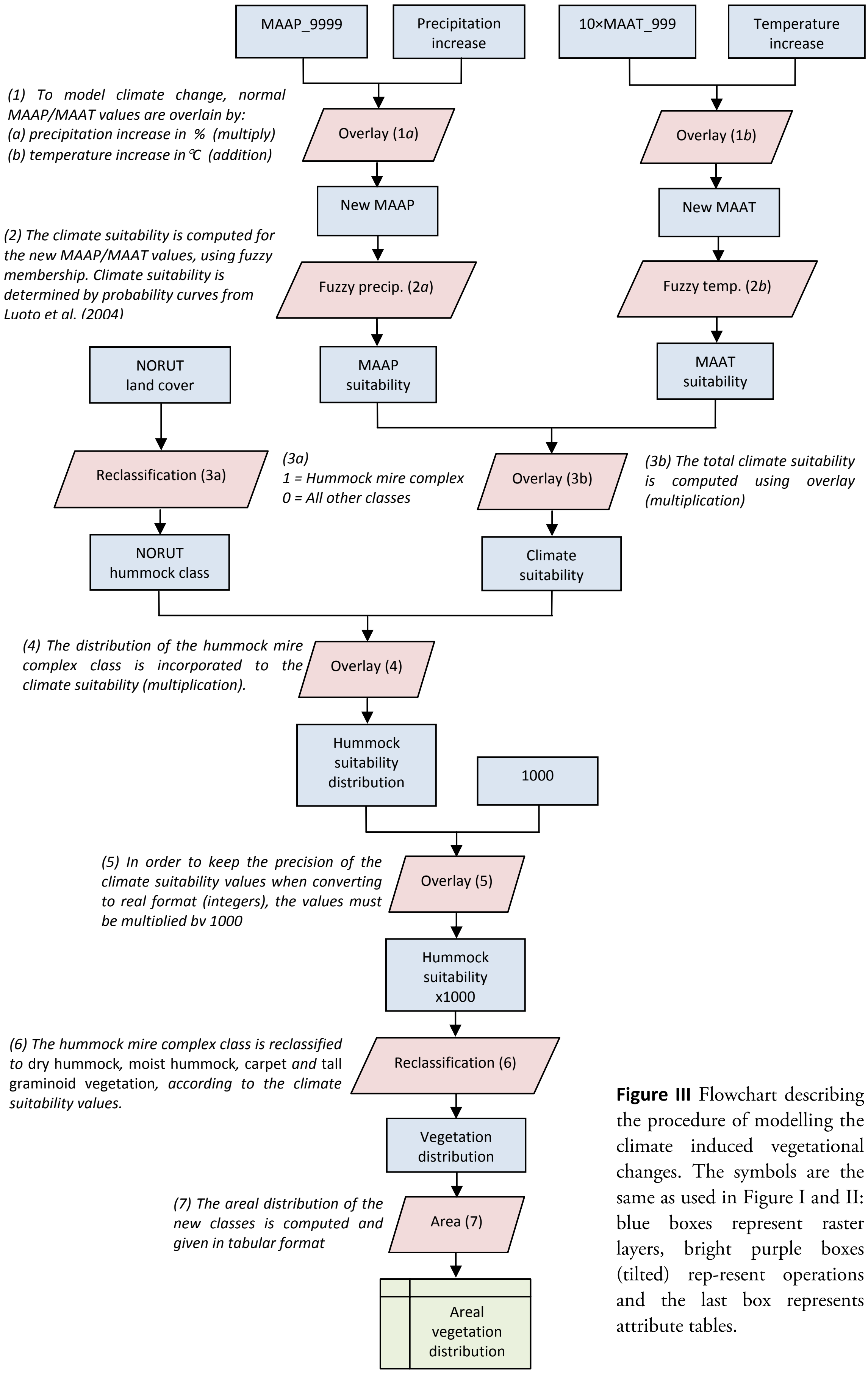

Figure III Flowchart describing the procedure of modelling the climate induced vegetational changes. The symbols are the same as used in Figure I and II: blue boxes represent raster layers, bright purple boxes (tilted) rep-resent operations and the last box represents attribute tables.

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