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Rapid responses of permafrost and vegetation to experimentally increased snow cover in sub-arctic Sweden

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Abstract
Increased snow depth already observed, and that predicted for the future are of critical importance to many geophysical and biological processes as well as human activities. The future characteristics of sub-arctic landscapes where permafrost is particularly vulnerable will depend on complex interactions between snow cover, vegetation and permafrost. An experimental manipulation was, therefore, set up on a lowland peat plateau with permafrost, in northernmost Sweden, to simulate projected future increases in winter precipitation and to study their effects on permafrost and vegetation. After seven years of treatment, statistically significant differences between manipulated and control plots were found in mean winter ground temperatures, which were 1.5 °C higher in manipulated plots. During the winter, a difference in minimum temperatures of up to 9 °C higher could be found in individual manipulated plots compared with control plots. Active layer thicknesses increased at the manipulated plots by almost 20% compared with the control plots and a mean surface subsidence of 24 cm was recorded in the manipulated plots compared to 5 cm in the control plots. The graminoid *Eriophorum vaginatum* has expanded in the manipulated plots and the vegetation remained green longer in the season.

Keywords: snow manipulation, sub-arctic permafrost, active layer thickness, vegetation changes

1. Introduction

Snow covers vast land areas for long periods of the year and is of critical importance to many geophysical and biological processes as well as human activities (Callaghan *et al* 2011a, 2011b). During the last few years, snow cover duration has decreased in many areas in the Arctic resulting in significant reductions in May and June snow cover extent (Derksen and Brown 2012). The snow cover duration is expected to continue to decrease while in some parts of the Arctic, snow depth (expressed as water equivalent) is expected to increase (Brown and Mote 2009). Snow has been identified as the single most important mesoscale variable that controls biological systems in Arctic ecosystems (Chernov 1985,

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Walker *et al* 1993). Snow cover, vegetation and the presence of an insulating organic layer are the most important factors accounting for variations in ground temperatures that control the state of permafrost (Romanovsky *et al* 2010, Desrochers and Granberg 1988). In general, fresh snow acts as an insulator and it reduces large energy losses from the surface in winter (Goodrich 1982, Williams and Smith 1989). Such insulation protects vegetation but may lead to permafrost degradation. In addition, when melted, snow can add water and alter the thermal conductivity of the soil that is of importance for permafrost (e.g. Romanovsky and Osterkamp 2000) and provides water and nutrients for vegetation (e.g. Aerts *et al* 2006, Schimel *et al* 2004). Snow depth and duration exert a significant direct control on fluxes of CO_2 in natural communities (Fahnestock *et al* 1998, Larsen *et al* 2007, Nobrega and Grogan 2007, Groendahl *et al* 2008) and also an indirect control through thawing of permafrost that exposes old organic material to enhanced decomposition and mineralization processes (e.g. Dorrepaal *et al* 2003, Keuper *et al* 2012).

In the Abisko area, in northernmost Sweden, there has been an increasing trend in snow depth during the last century of about 2–3 cm per decade in December–February (Kohler *et al* 2006), although within the last decade, there has been a decrease (Callaghan *et al* 2010). Downscaled climate scenarios for the Abisko region predict an increase in precipitation by 1.5–2% per decade for the coming 70 years (Sælthun and Barkved 2003). This precipitation increase is expected to be twice as high in winter/autumn than in summer. The projected increases in winter precipitation are mainly expected to occur due to increasing surface temperatures of the northern Atlantic Ocean and these are likely to cause higher evaporation and subsequently increased snow fall in northern Fennoscandia (Seppälä 2003).

The observed changes in snow cover have affected peat mires with permafrost in sub-arctic Sweden. Evidence comes from thawing permafrost, increases in active layer thickness and associated vegetation changes that have been reported during the last decade (Akerman and Johansson 2008, Christensen *et al* 2004, Malmer *et al* 2005, Ström and Christensen 2007, Johansson *et al* 2006b). A shallow snow layer has been critical for the preservation of permafrost in these peat mires which are located at the mean annual isotherm of 0 °C. With the snow cover increases predicted for the future, it is likely that the process of permafrost degradation (Akerman and Johansson 2008, Johansson *et al* 2011) will continue or even accelerate in the area. As a consequence, ecosystem structure such as plant species composition, and function, for example trace gas fluxes, are likely to change even further than already observed (Malmer *et al* 2005, Bosiö *et al* 2012).

Permafrost is a component of a complex geo-ecological system with both positive and negative feedbacks operating among changes in snow, vegetation, soil properties and permafrost itself (Shur and Jorgensen 2007). Vegetation affects permafrost through for example insulation, its albedo and through trapping of snow (Sturm *et al* 2001), whereas permafrost affects vegetation by limiting the depth of soil where seasonal biological activity is possible, reducing rooting zones as well as soil temperatures and preventing drainage (Shaver and Cutler 1979). To be able to predict such future changes, it is necessary to study both vegetation and permafrost, as the impact of climate change on permafrost is both direct and indirect associated with vegetation dynamics.

Although snow manipulation experiments have been set up in different parts of the Arctic to look at the effects of increasing snow cover and duration on vegetation (see references in review by Wipf and Rixen 2010, Natali *et al* 2011) or on permafrost (e.g. Nicholson 1978, Seppälä 2003, Hinkel and Hurd 2006), many of the studies are short term and do not integrate the effect on vegetation and permafrost together. In contrast, our study is long term and examines the integral of snow–permafrost–vegetation interactions that are essential to understand the complete system. We present results from a 7-year snow manipulation experiment in a peat mire where we simulate a future scenario of increased winter precipitation predicted for the Abisko area and focus on the responses of both vegetation and permafrost.

2. Material and methods

2.1. Study site

The snow manipulation experiment was established in autumn 2005 on a peat plateau within a mire complex called Storflaket (68°20′48″N, 18°58′16′E), approximately 6 km east of the Abisko Scientific Research Station in northernmost Sweden (figure 1(a); table 1). The mire is 900 m long and 400 m wide and is divided into a western and eastern part by a man-made depression with standing water (for drainage). The peat plateau is elevated above the surrounding area and contains permafrost with a high content of segregated ice that extends downward into the underlying mineral soil. The Storflaket mire was chosen as it was a fairly homogeneous, undisturbed and intact plateau, in contrast to other peat plateaus in the area where permafrost degradation is more advanced. The mire borders a sparse birch (*Betula pubescens* ssp. *czerepanovii*) forest to the east and west, a railway in the south and the main road (E10) in the north. Further characteristics of the mire are presented in table 1.

The Abisko area is situated in a rain shadow and the total annual precipitation was 304 mm for the period 1961–1990 (Alexandersson *et al* 1991). However the total annual precipitation has increased since then and for the period 1997–2007 it was 362 mm (Abisko Station meteorological data; www.polar.se/abisko). The mean annual air temperature was −0.6 °C for the period 1913–2006, and has increased by 2.5 °C during this period. This has resulted in mean annual air temperatures being above 0 °C during the last decade (Callaghan *et al* 2010).

According to Brown *et al* (1998), the Abisko area lies within the zone of discontinuous permafrost. However, with the observed permafrost degradation during the last decade (Akerman and Johansson 2008, Johansson *et al* 2011) the area is now more characteristic of the 'sporadic permafrost' zone. Permafrost is widespread in the mountains above

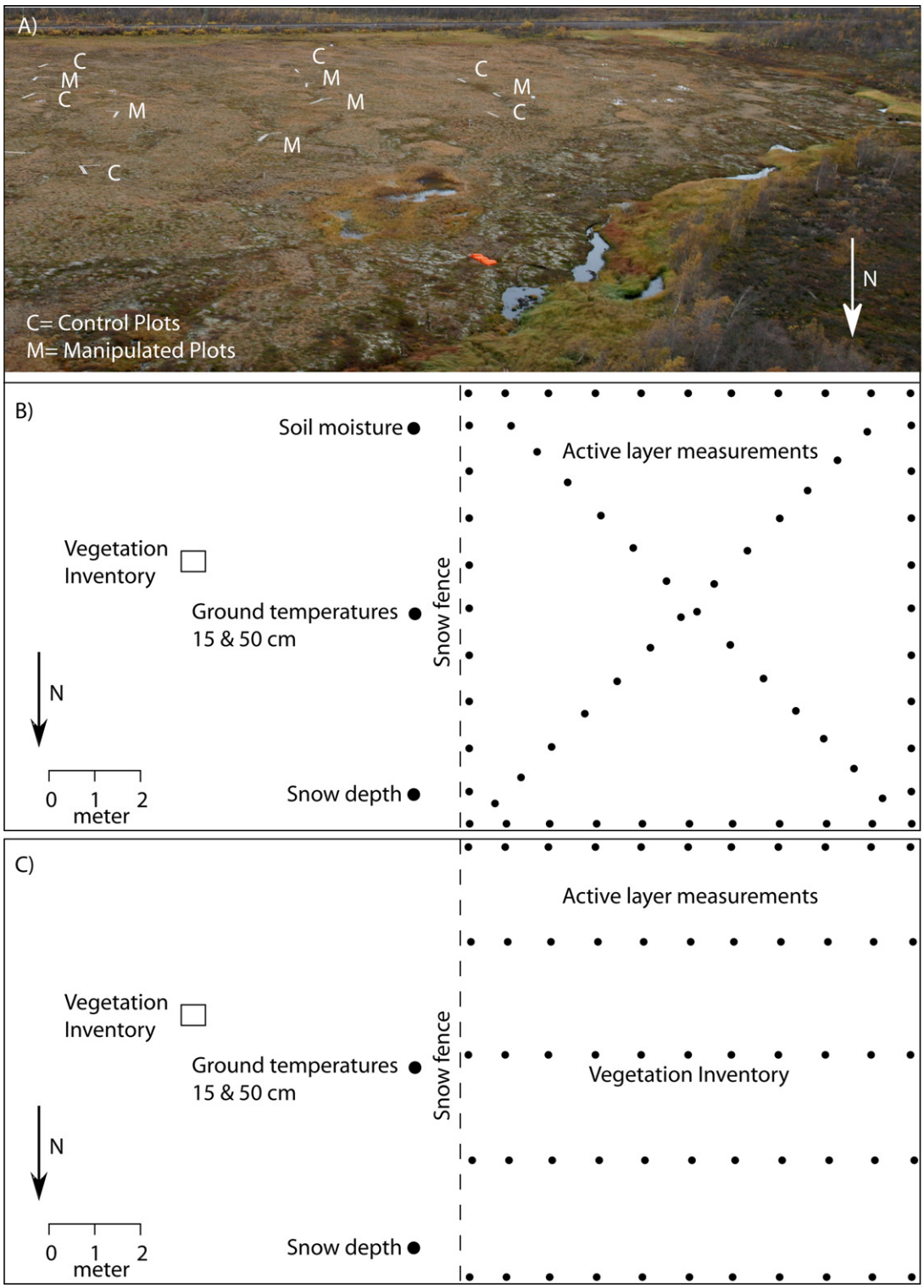


Figure 1. The experimental design (A) the location of the 12 plots with and without snow fences on the mire. Photo J Åkerman (B). The design for each individual plot with and without a snow fence for the period 2005–2008 and (C) the improved design for each individual plot with and without a snow fence for the period 2009–2012.

approximately 850 m.a.s.l. on the northeast- and east- facing slopes and above 1100 m.a.s.l. on the south-facing slopes (Ridefelt *et al* 2008). At lower elevations permafrost is restricted in distribution to peat mires (Johansson *et al* 2006a). The permafrost at the study site is 'ecosystem protected permafrost' in the sense of Shur and Jorgensen (2007: see table 1 for further details). This type of permafrost was formed under climates colder than present but can persist as sporadic patches under a warmer climate due to the peat mire ecosystem's properties (such as soil thermal

Table 1. Site-specific information for the Storflaket mire.

Variables	Value	Reference
Mean annual air temperature—2 m (2006–2011)	0.2 °C	Recorded during this study
Mean snow depth (November–April; 2005–2012)	∼10 cm	Recorded during this study
Thickness of permafrost	>16 m	Akerman and Johansson (2008), Dobinski (2010)
Mean thickness of active layer (1978–2012)	60 cm	Updated from Akerman and Johansson (2008)
Mean ground temperature at 5 m depth (2008–2011)	−0.5 °C	Johansson *et al* (2011)
Thickness of organic layer	60–90 cm	Klaminder *et al* (2008)
Visible ice content (1980–2000)	Average 7–8%, 35% of this was found in the upper permafrost body	Akerman and Johansson (2008)
Dominating species on the mire	Dwarf shrubs: *Andromeda polifolia, Vaccinium uliginosum, Empetrum nigrum* and *Betula nana* Mosses: *Dicranum scoparium*, *Sphagnum fuscum* and *Sphagnum balticum* Lichens: *Cetraria cucullata, Cetraria nivalis* and *Cladonia* spp. Graminoids: *Eriophorum vaginatum* In addition, *Rubus chamaemorus*	The nomenclature of the vascular plants, mosses and lichens follows Mossberg (1992), Nyholm (1954) and Santesson (1993) respectively.

conductivity). 'Ecosystem protected permafrost' is typically found in climates where current mean annual air temperature is approximately 2 °C to −2 °C (Shur and Jorgensen 2007).

2.2. Experimental set up

The experimental manipulation was established on the western part of the plateau in 2005. Twelve as homogeneous-as-possible plots were established and measurements were made of active layer thickness, species composition, temperatures of soil (at 15 and 50 cm depth) and air (at 2 m height), soil moisture and snow depth (figure 1). Six of the twelve sites were randomly chosen to be manipulated plots. Manipulations consisted of erecting snow fences (10 m long and 1 m tall) before the snow onset (late September to mid October) and removing them at the end of the snow season after the snow melt (end of May/beginning of June). The snow fences were erected perpendicular to the dominant wind direction (westerly and easterly winds). The snow fences were removed during summer to avoid damage to and by reindeer that frequently visit the mire and to avoid any possible shading effects. The other six sites without snow fences were control plots. As more or less similar snow accumulation was expected on both the eastern and western sides of the snow fence (due to the two dominating wind directions), we applied the monitoring scheme at both sides of the snow fence. This avoided the measurements of one parameter affecting the measurements of another parameter. In the beginning of winter, snow accumulated more on the western side of the snow fence than on the eastern side. Later in the season the snow accumulation was evenly distributed over both the eastern and western sides of the snow fence as expected. Even though ground temperatures, snow depth and vegetation are monitored on the eastern side of the snow fence, this uneven distribution of snow accumulation in the beginning of the season only affected the monitoring of vegetation. The measurements of snow and ground temperatures were made very close to the snow fence that experienced similar conditions to the western side so the uneven distribution of snow was not a problem.

2.3. Variables monitored

Snow depth was recorded manually once per month at all 12 plots during all but two (2007–2008 and 2010–2011) winter seasons. In addition, daily recordings were made at one control and one manipulated plot, using a remote digital camera, model RDC365 produced by Metsupport Aps, Denmark. At both sites there was a 1 m stick where every 10 cm was marked to enable daily recording of snow depth. The RDC also recorded snow onset and snow melt (2007–2008). Due to technical problems, these recordings were only made during the first three years of the project. For 2011 and 2012, date of snow melt has been recorded by PAR sensors, see Bosiö *et al* (2013) for further info on method.

Soil temperatures were recorded at 15 cm depth at all 12 plots. At one control and one manipulated plot they were also recorded at 50 cm. The temperature was recorded hourly using TinyTag loggers (Tinytag Plus 12G). The precision of the measurements was ±0.2 °C. Air temperature was recorded hourly using a TinyTag logger located in a radiation shield to avoid any artefacts due to direct solar radiation.

The active layer thickness measurements were conducted annually during the second week of September, to monitor the maximum thaw depth. During the first four years of the experiment (2005–2008), measurements were made at 66 sample points in each plot (see figure 1(B)). Between 2009 and 2012, an improved sampling scheme was used to better record the ongoing changes, using fewer sampling points (55) but with a better spatial distribution (figure 1(C)). The thaw depth was determined by mechanical probing. A 1 m long, 1 cm diameter graduated steel rod was inserted into the soil to the depth of resistance to determine the active layer thickness. The length of the probe (1 m) was not sufficient in 2012 for several sampling points at the manipulated plots that had a thaw depth greater than 1 m.

Surface subsidence was recorded at all 12 plots in summer 2012 by measuring the distance from the ground in the middle of the plot to a tight steel measuring tape that was placed horizontally on top of the surrounding surface outside of the plots.

Soil moisture (volumetric soil water content) was measured using a handheld ML2x ThetaKit (Soil Moisture Measurement Kit) on several occasions. The rods were inserted vertically 6 cm into the ground. The accuracy of the measurements was ±1%.

Vegetation inventories were carried out at 50 points at each of the twelve plots using the point intercept method (Jonasson 1988) in a 50 cm × 50 cm grid. The data was then classified into three plant functional types; graminoids, dwarf shrubs and mosses and lichens as they will affect ground temperatures in different ways (Blok *et al* 2010, 2011, Yi *et al* 2007). As the vegetation inventories were made on the east side of the plots and all effects are seen on the western side of the plot, an additional transect was established in the middle of the plot on the western side (figure 1(C)) in 2011. The species present and the height of *Eriophorum vaginatum* were recorded every 1 m.

2.4. Statistical analyses

Data was analysed using the statistical software SPSS ver.17.0. Normal distribution of the data was tested using a nonparametric test (one sample Kolmogorov–Smirnov). The general linear model (repeated measures test) was used to determine if there were any statistically significant differences between the control plots and the manipulated plots for the various parameters monitored.

3. Results

The fences accumulated additional snow and the thickness was statistically significantly greater ($p < 0.001$) at the manipulated plots compared to the control plots (figure 2). The mean winter (November–April) snow depth for the period 2005–2012 was 8 cm (ranging from 6 to 9 cm) at the control plots. At the manipulated plots the mean winter snow depth was 21 cm (ranging from 16 to 24 cm).

The snow accumulation at the manipulated plots was not evenly distributed over the winter season. In late autumn, snow accumulation was mainly found on the western side of the plots while in spring there was in general a more even distribution of the snow over the whole plot (i.e. on both sides of the snow fence). The snow onset date varies among the years and ranges from mid October to mid November (Abisko Scientific Research Station weather data; www.polar.se/abisko) but was similar for all plots. The date of snow melt also varies over the years, but was different between the control and manipulated plots. For example, in 2007, snow had disappeared from the control plots by mid April but remained for another three weeks on the manipulated plots. A similar development was found in 2008 and 2011, when the snow melted from the control plots approximately 3 weeks earlier compared to the manipulated plots. In 2012, the snow disappeared late in the season (in early June) at both control and manipulated plots and there was only a three days difference in the date of snow melt (Bosiö *et al* 2013).

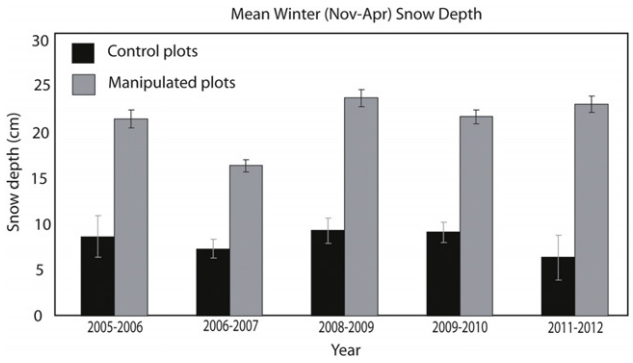


Figure 2. Mean winter (November–April) snow depth and standard error in the manipulated and control plots.

3.1. Impacts on ground temperatures

The additional snow cover on the manipulated plots increased the mean winter (November–April for the years 2005–2012) ground temperatures at 15 cm depth by 1.5 °C compared to the control plots (figure 3). The mean ground temperature in the control plots was −3.1 °C, while in the manipulated plots it was statistically significantly higher ($p < 0.001$) at −1.6 °C. The differences in ground temperatures are much larger when comparing individual plots. Minimum temperature in 2008 at two individual plots (one control and one manipulated) ranged from −13 °C in the control plot compared to only −4 °C in the manipulated plot. In contrast, in the summer (June–August), no statistically significant differences were found. At 50 cm depth, the manipulated plot was in general approximately 0.5 °C warmer in early May compared to the control plots. However, in the second half of June and beginning of July, there was no difference between the manipulated and control plots.

3.2. Impacts on active layer thickness and surface subsidence

At the outset of the experiment (in 2005) there was no statistically significant difference in active layer thickness between the control and the manipulated plots (figure 4). However, from the second year of treatment (in 2007), there was a statistically significant difference between the active layer thicknesses in the control plots compared to the

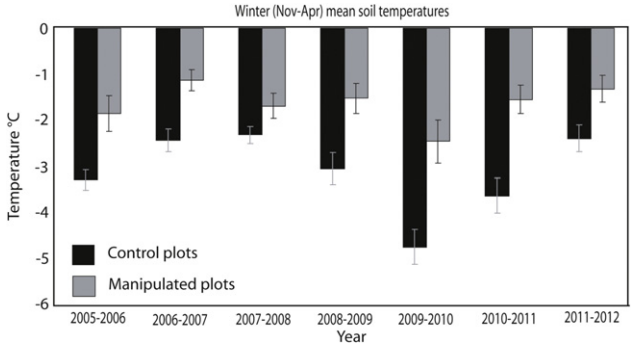


Figure 3. Winter (November–April) mean ground temperatures at 15 cm depth and standard error.

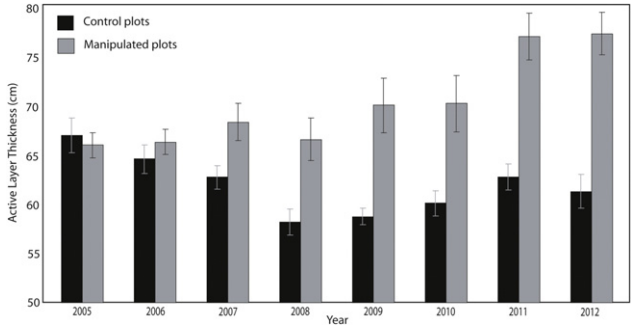


Figure 4. Mean active layer thickness and standard errors. (Note that measurements from 2005 were made at the outset of the experiment to record baseline information.)

manipulated plots. The active layer thickness at the control plots showed similar inter-annual variability as the CALM site (at the other part of the Storflaket mire) with active layer thickness ranging from 67 cm at the start of the experiment, to 58 cm in 2008 and then to 61 cm in 2012. At the manipulated plots, there has been a general increase in the active layer thickness from year to year. In 2005 the mean active layer thickness was 65 cm and in 2012 it was 77 cm. The difference between the control and manipulated plots is statistically significant ($p < 0.001$).

Surface subsidence was recorded in 2012 in all the manipulated plots after seven years of treatment. The mean subsidence was 24 cm (standard error ±2.8) compared to the surrounding environment. This created hollows of about 4 m × 8 m. In the control plots, the mean surface subsidence was 5 cm (standard error ±2.6). However, at three of the control plots, no subsidence could be detected.

3.3. Impacts on soil water content

The volumetric soil water content varied over seasons and between years. However, the manipulated plots were in general wetter than the control plots throughout the summer. This effect was especially noticeable just after snow melt, when the ground was still frozen and small ponds sometimes formed in the manipulated plots while no standing water accumulated in the control plots (figure 5). However, after only a few weeks, the ponds drained. The mean volumetric soil water content in September 2012 was 65% (standard error ± 9.6) at the manipulated plots compared to 36% (standard error ± 3.9) at the control plots.

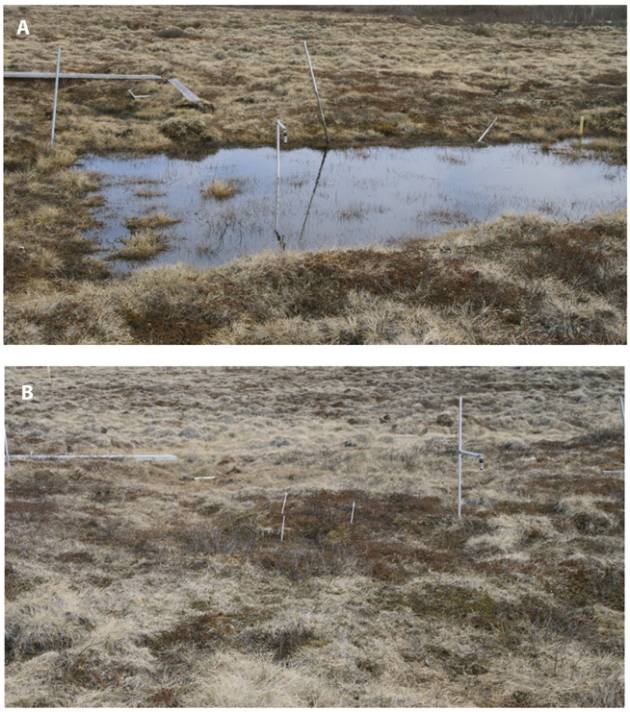


Figure 5. (A) Water logged manipulation plot on 11 May 2011. (B) Control plot on the same day (photo: F Löfberg).

3.4. Impacts on vegetation

No statistically significant difference in the abundance of plant functional types could be detected between the manipulated and the control plots. However, at the manipulated sites the graminoid *Eriophorum vaginatum* have more flowering tillers and are higher compared to the control plots (figure 6). This species dominates the manipulated plots, even though all the original species were still present in 2012. In 2011, the mean height of Eriophorum vaginatum was 24 cm (standard error ± 1.9) in manipulated plots compared to 13 cm (standard error ± 0.7) in the control plots. In 2012, the mean height was 28 cm (standard error ± 2.5) at the manipulated plots and 18 cm (standard error ± 0.5) at the control plots (figure 6(B)).

At the end of summer (August and September) during the five years 2008–2012, the vegetation was still green in the manipulated plots compared to the rest of the mire that had turned into the brownish autumn colours.

4. Discussion

4.1. Snow accumulation

Downscaled future scenarios for the study area indicate an increase in precipitation of 18% by the year 2080 and the precipitation increase in winter/autumn is expected to be twice as high as in summer (Sælthun and Barkved 2003). An increase in snow depth has been reported from the study area during the last Century (Kohler *et al* 2006) apart from the last decade (Callaghan *et al* 2010). The snow depth increased by the experiment reported here is twice as high as in the control plots, which is much more than the average increase

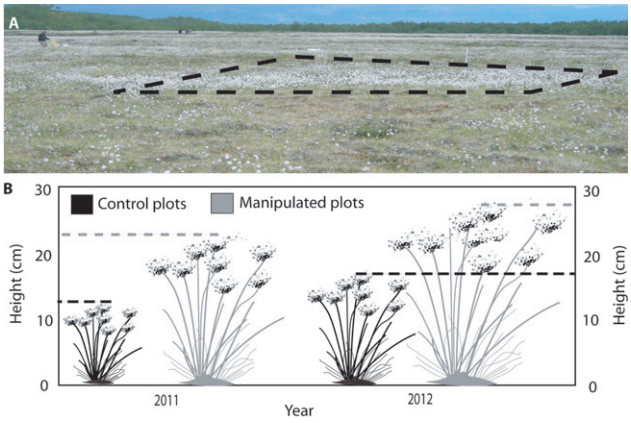


Figure 6. (A) Denser flowering tiller of *Eriophorum vaginatum* in the manipulated plots compared to the rest of the mire and (B) the height of *Eriophorum vaginatum* in control and manipulated plots for 2011 and 2012.

in winter precipitation predicted by the end of the century (Sælthun and Barkved 2003). Despite this, the manipulation experiment could be a likely scenario for parts of the mire as thawing permafrost is accompanied by heterogeneous surface subsidence that creates hollows which will trap additional snow due to the wind drift in the wider open areas.

In late autumn, snow accumulation mainly occurred on the western side of the plots while in spring there was in general a more even distribution of the accumulated snow over the whole of each manipulated plot (i.e. on both sides of the snow fence). The observed changes in ground temperatures, active layer thickness and vegetation have all occurred close to and on the western side of the snow fence rather than on the eastern side. This demonstrates the great importance of the timing of snow accumulation in autumn in sub-arctic conditions. This pattern has previously been demonstrated in a high arctic environment by Lafreniere *et al* (2013).

4.2. Impacts on ground temperatures

The increases measured in winter ground temperatures are a direct effect of the insulting capacity of the snow. These temperature increases are in line with those achieved in other snow manipulation experiments in Abisko (Dorrepaal *et al* 2003), in northern Finland (Seppälä 2003) and from the northern foothills of Alaska range (referred to as the CiPEHR site hereafter, Natali *et al* 2011). At snow manipulation experiments in Barrow and Toolik Lake, Alaska, much larger increases in winter ground temperatures were found (between 6 °C and 14 °C and 15 °C respectively; Hinkel and Hurd 2006, Walker *et al* 1999). These were however most likely the result of much taller snow fences (4 and 2.8 m tall) resulting in much thicker snow deposits and hence the higher temperature increases.

The lack of statistically significant differences in ground temperatures in summer between the manipulated and the control plots are partly because ground temperatures were recorded at a shallow depth (15 cm) in the active layer. These shallow depths are more affected by air temperatures compared to deeper levels. At two sites, temperatures were also recorded at 50 cm depth and here a prolonged effect of the winter warming lasted until the middle to the end of June and in some years even to the beginning of July in the manipulated plot compared to the control plot. The lack of difference in summer temperatures was also due to the timing of snow melt. Seppälä (2003) reported lower mean summer ground temperatures in the experimental plot compared to the control plot (there was no replication in the experiment) of a snow manipulation experiment in northern Finland. This was due to a thick snow cover that persisted several weeks or months after the surrounding area was snow-free. The differences at our plots in ground temperatures that were recorded during winter but not in summer have most likely been evened-out during late spring/early summer when the control plots were snow-free and the manipulated plots still had snow. At the CiPEHR site in Alaska, warming effects continued in the manipulated plots into July and August 2010 when deep soil (40 cm) temperatures were 1.3 °C higher than in the control plots (Natali *et al* 2012). At this experiment, the snow was removed from the plots before snow melt in early spring to ensure comparable melt-out dates between control and manipulated plots which explains the difference in temperatures in summer. In contrast in our experiment, the earlier snow melt in the control plots resulted in a decreased difference compared to the manipulated plots through a more rapid warming in spring.

4.3. Impacts on active layer thickness and surface subsidence

Active layer thickness has increased due to the increased ground temperatures in the lower part of the active layer. The resulting subsidence creates hollows that increase soil moisture which in turn alter the soil thermal conductivity of the peat and that acts as a positive feedback accelerating the increase of thickness in the active layer. At the CiPEHR site (Natali *et al* 2012) and in Toolik Lake (Nowinski *et al* 2010) in Alaska, active layer thickness increased as a result of the additional snow accumulation and which reduces large energy losses from the surface in winter. In contrast, Hinkel and Hurd (2006) reported from Barrow, Alaska, that no difference could be found between the average thaw depth on the manipulated and the control plots but in Finland, Seppälä (2003) reported a decrease in active layer thickness at the manipulated plots. The lack of difference in Alaska and the decrease in active layer thickness in Finland can be explained by differences at the two sites in the lengths of the reduced thaw seasons.

The surface subsidence observed in the manipulated plots was caused by the increasing active layer thickness and the melting of segregated ice that is common in the upper part of the permafrost in this peat plateau (Akerman and Johansson 2008). Similar surface subsidence but at a slower rate has been observed on several peat plateaus in the Abisko area as a result of natural permafrost degradation (Akerman and Johansson 2008). Similar subsidence was reported from Barrow, Alaska, by Hinkel and Hurd (2006) who after 6 years of treatment detected local ground subsidence of between 10 and 20 cm.

4.4. Impacts on soil water content

As the soil water content was higher in the manipulated plots compared to the control plots throughout the summer, the increase in surface water content is very likely to be due to the effects of the local surface subsidence rather than from additional water from snow melt. Similar findings were made at the CiPEHR site in Alaska by Natali *et al* (2011) who reported higher monthly surface soil water content throughout the summer in the manipulated plots, even though the snow in the manipulated plots was removed before snow melt in spring.

4.5. Impacts on vegetation

The graminoid, *Eriophorum vaginatum*, benefitted from the increased snow accumulation on the western sides of the snow fences. Measurements showed that tillers were much higher and visual observation showed that they were denser at the manipulated plots compared to the control plots. This was likely caused by higher soil water content and a release of nitrogen stored in permafrost: plant production in peat plateaus such as Storflaket is often nitrogen-limited (Keuper *et al* 2012). These results agree with findings by Malmer *et al* (2005) from a peat plateau 4 km east of Storflaket. They reported the expansion of graminoids where natural permafrost degradation had occurred. Similar observations were made from experiments at Toolik Lake in Alaska where Wahren *et al* (2005) found that the vegetation cover of graminoids, especially *E. vaginatum*, increased. In addition, similar findings were made at the CiPHER site in Alaska where the above ground net primary productivity of *E. vaginatum* increased (Natali *et al* 2012). Although the results from the Alaskan sites were comparable to ours, a review of papers on snow manipulation experiments in Arctic and alpine tundra ecosystems by Wipf and Rixen (2010) present a different general pattern. Wipf and Rixen (2010) concluded that increased snow accumulation resulted in a decrease in productivity and abundance. This effect is most likely to be observed where the snow accumulation is sufficient to significantly reduce the length of the growing season. For example, Borner *et al* (2008) showed from Toolik Lake, that *E. vaginatum* declined in the deepest parts of the snow drift in the same experiment that reported increase in vegetation cover of the same species in more moderate snow accumulation areas.

Visual observations at our manipulation sites showed an increase in greenness for the plots with a snow fence compared to the control plots in the end of the summer. Similar results were observed at the snow manipulation experiment in Barrow, Alaska (Hinkel and Hurd 2006) whereas at Toolik Lake, Alaska no differences in greenness between plots with snow fences and the control plots were detected (Walker *et al* 1999).

The complexity of interactions under various climate change scenario between snow depth, snow cover duration, soil moisture content, active layer dynamics and vegetation is substantial. However, the net outcomes are very important for ecosystem services and need to be better understood.

5. Conclusions

The seven years snow manipulation experiment has impacted both permafrost and vegetation on the peat plateau in sub-arctic Sweden. Ground temperatures have increased by 1.5 °C, active layer thickness has increased by 20% (16 cm in 2012) and surface subsidence has occurred at all the manipulated sites by as much as 35 cm. Soil water content increased in the manipulated plots and the live vegetation cover of the graminoid *Eriophorum vaginatum* increased. The effects of the additional snow cover in winter are both direct and indirect. As an example, the snow accumulation directly increases ground temperatures by reducing large energy losses from the surface in winter. As a consequence, the active layer thickness increases, segregated ice melts, resulting in indirect effects such as surface subsidence, increases of soil water content mainly due to the subsidence. In addition, the increased soil water content increases the soil thermal conductivity of the peat which further increases the ground temperatures in summer. A critically important direction for future experimental research is to explore future scenarios of snow cover in which snow water equivalent increases in winter but snow cover duration decreases. The interaction between the hydrological implications of such a scenario in winter and various precipitation regimes in summer will determine landscape processes, biodiversity, ecosystem services and trace gas fluxes.

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