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Effect of simulated disturbance by geese on soil temperature and active layer thickness over one growing season

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Northern Populations and Ecosystems

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Abstract

The Arctic is an area predicted to be strongly affected by climate change, and the extent of permafrost is expected to decrease. The insulating capacity of bryophytes is central in permafrost preservation. In High-Arctic Svalbard, disturbance by geese through grubbing may damage and remove parts of the bryophyte layer in moss tundra. The disruption is expected to lead to increased soil temperatures and shift the vegetation from being dominated by bryophytes to graminoids.

This study focuses on how simulated grubbing affects soil temperature and active layer thickness (ALT) over one growing season. The data were collected in central Adventdalen, Svalbard, in a landscape dominated by ice-wedge polygons. Each polygon was characterized by a wet bryophyte-covered centre encircled by a transitional middle part and a dry rim dominated by vascular plants. Plots were established in each part of six polygons and goose grubbing applied manually to each plot in three polygons after snowmelt, while three polygons were left as controls. Organic and moss layer thickness, soil moisture, soil temperature and ALT from each plot were sampled over the season.

The plots exposed to simulated grubbing were expected to show an increase in soil temperature and deepening of ALT compared to the control plots. The effect was expected to be stronger earlier in the season and mitigated by a deeper organic and bryophyte layer. No significant effect of grubbing was registered on soil temperature nor ALT, but the plots covered by a deeper layer of bryophytes and organic soil had lower soil temperature and ALT than the other plots. Future research should investigate disturbance at a larger scale over multiple years.

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Definitions and abbreviations

active layer The soil layer above permafrost which thaws and freezes each year.

ALT Active Layer Thickness

grubbing Foraging by geese, where they use their beaks to dig for rhizomes, roots and shoots below ground, resulting in disruption of the vegetation and moss layer.

OLT Organic Layer Thickness, for practical reasons here combined with the bryophyte layer thickness.

permafrost Ground with a temperature at or below 0°C for at least two consecutive years.



Introduction

1.1 Permafrost and active layer thickness

Most of the terrestrial area in polar regions is underlain by permafrost (Biskaborn et al., 2019), defined as ground staying at or below a temperature of 0°C for at least two consecutive years. Its stability is sensitive to climate change effects, in particular temperature and soil hydrology (Biskaborn et al., 2019). Over the last decades, the permafrost layer has been documented to thaw (Lachenbruch and Marshall, 1986). Between 2007 and 2016, the global permafrost temperature increased by 0.29°C (Biskaborn et al., 2019) and the extent of near-surface permafrost is predicted to reduce by 2100 (Constable et al., 2022). Permafrost in the High-Arctic archipelago of Svalbard has the highest temperatures in these latitudes, and is therefore particularly vulnerable to temperature increase (Hanssen-Bauer et al., 2019).

Each summer, the top layer of the frozen ground thaws. This layer is defined as the active layer, and its depth is dependent on complex mechanisms between environmental factors. As temperatures rise, the active layer thickness (ALT) increases (Grünberg et al., 2020), a trend which is expected to continue over the next decades (Constable et al., 2022). Locally, ALT variation is related to microtopography (Abolt et al., 2018). Ridges are often wind blown and will therefore have less vegetation and a shallow snow layer, while depressions in the ground tend to accumulate a deeper snow pack, increasing the soil moisture content as it melts, and causing a deeper organic layer to accumulate. Combined, these factors influence the depth of the ALT (Grünberg et al., 2020).

1.2 Impact of climate change

The effect of climate change is strong in the Arctic compared to lower latitudes (Shaver et al., 1992), and many effects are already observable in Svalbard. A report by the Norwegian Environmental Agency on the prediction of the future climate in Svalbard (Hanssen-Bauer et al., 2019), estimates the average temperature to rise by 10°C by year 2100 in response to global warming. Additional environmental predictions from this report point to less freezing days in summer and unstable winters with more frequent periods of temperatures above 0°C within this century. Precipitation is likely to increase by about 65%, and may fall as snow or rain depending on temperature. Climate factors such as these are likely to impact the permafrost (Atchley et al., 2016). ALT in sedimentary Adventdalen has increased by 0.6 cm since 2000, while in areas with rocky ground ALT has increased by several centimetres. However, under future climate scenarios, ALT is expected to increase by several meters by year 2100 (Hanssen-Bauer et al., 2019).

In permafrost, large amounts of carbon originating from the accumulation of organic material over millennia is locked in the frozen soil (Shaver et al., 1992). Permafrost thaw is expected release this organic material as methane and carbon dioxide, and thus further increase global temperatures by forming a positive feedback mechanism (Schuur et al., 2015). Details concerning these feedbacks are still unknown and their impacts have not yet been fully incorporated into models on future climate scenarios (Natali et al., 2021).

1.3 Organic layer and vegetation

Soil temperature increases may be mitigated by an insulating layer of organic soil and bryophytes (Schuur et al., 2008, 2015). Unlike vascular plants, which decrease in distribution and species numbers at higher latitudes, bryophytes cover an extensive part of the Arctic ecosystem (Pointing et al., 2015). They have various functional roles in the ecosystem, such as providing nutrition for herbivores, building up an organic layer for plant establishment and they play an important part in biogeochemical cycles (Lett et al., 2021). Bryophytes tend to form a thick layer which insulates and protects the soil and permafrost. The physical properties of the moss mat provides a high water content, which strongly improves the heat capacity of soil (Gornall et al., 2007). Ground with high heat capacity requires more energy to increase in temperature. Thus, bryophyte mats reduce soil temperature amplitude and the number of freeze-thaw events in Arctic landscapes (Soudzilovskaia et al., 2013).

Due to the low thermal conductivity of peat compared to mineral soil, organic

layers with high peat contents act as effective insulators during summer. Additionally, frozen peat requires more energy to thaw, leading to the formation of a more shallow ALT in the ground beneath compared to that found in mineral soil (Atchley et al., 2016). The abundance of tundra bryophytes appears to decline in response to higher temperatures, in favour of vascular plants (Elmendorf et al., 2012). The persistence of deep bryophyte layers, which currently provide stability for the Arctic permafrost, is thus likely to be vulnerable to climate change (Lang et al., 2012). Consequently, as deeper bryophyte layers are shown to reduce soil temperatures and fluctuations; disturbance and destruction of the bryophyte layer are expected to influence soil temperatures (Gornall et al., 2007). There is, however, limited research on the direct effect disruption of the bryophyte layer could have on soil temperature, and consequently ALT.

1.4 Disturbance from herbivores

In combination with the effect of increased temperatures on the expansion of vascular plants in Arctic ecosystems, disturbance from herbivores may further drive the vegetation towards graminoids at the expense of bryophytes (Ravolainen et al., 2020). The tolerance of graminoids to herbivore disturbance is higher than that of bryophytes, and they benefit from the addition of nutrients herbivores provide (Van der Wal and Brooker, 2004). The joint effect of herbivory and higher soil temperatures is consequently expected to drive colder moss-dominated ecosystems to ecosystems with higher soil temperatures, deeper active layer, and a reduced capacity to retain soil water (Ravolainen et al., 2020; Van der Wal, 2006).

Currently, one of the herbivores with the most extensive ecological impact on Svalbard is the pink-footed goose (*Anser brachyrhynchus*). The population of pink-footed geese has increased rapidly over the last decades, and more than doubled from about 40 000 individuals in year 2000 to about 80 000 in 2020 (Heldbjerg et al., 2020). This escalation in numbers can be explained by the increased conservational efforts and changes in agriculture at the wintering grounds of pink-footed geese on the European continent (Fox et al., 2005). Combined with higher temperatures in their Arctic feeding and breeding grounds, the nesting success of pink-footed geese has improved (Descamps et al., 2017). Geese in the Arctic tundra feed by a technique named grubbing, where they use their beaks to dig for rhizomes, roots and shoots below ground. This results in damage to the vegetation and disrupts the bryophyte layer. The smaller barnacle geese (*Branta leucopsis*) are also common feeders in Svalbard, but they do not have the capability to grub with the same intensity as the pink-footed geese (Van der Wal et al., 2020). In Svalbard, pink-footed geese

primarily grub for roots, rhizomes and stems of grasses and sedges such as *DuPontia* spp. and *Eriophorum scheuchzeri* ssp. *alpestre*, in addition to *Bistorta vivipara* and *Equisetum arvense* ssp. **alpestre**. They mainly grub just after the snow has melted (Anderson et al., 2012; Fox et al., 2006). Spring is also the time of year when soil temperature and ALT is documented to show the greatest spatial variation, while it is more stable in late season (Grünberg et al., 2020). Damage from grubbing may therefore influence soil temperatures and consequently ALT in areas exposed to high levels of grubbing, but how this impact varies over the season is uncertain.

Grubbing may disrupt moss layers, including the vascular plants growing there, entirely. If the disturbance becomes too intense, it has the potential to damage vegetation to the extent where it is unable to recover before the following season. New grubbing is then resumed, further destroying the already vulnerable ground (Jefferies and Rockwell, 2002). These kinds of severe cases of damage from grubbing are documented in the Canadian Arctic. Here, the population of the lesser snow goose (*Chen caerulescens caerulescens*) has increased rapidly, destroying the vegetation and generating large areas of bare ground (Kotanen and Jefferies, 1997). After being exposed to intense grubbing, communities which have previously been graminoid-dominated enter a state of bare sediment. Consequently, these areas have become more prone to erosion and less resistant to physical disturbance (Abraham et al., 2005).

Likewise, in Svalbard, effects of grubbing are becoming evident. Fragmented areas often cover several square metres (Speed et al., 2009), and NDVI recordings show variation in reflectance between grubbed and non-grubbed sites (Eischeid et al., 2021). This response is visible within larger regions, indicating that grubbing has the potential to impact at landscape scale (Speed et al., 2009; Eischeid et al., 2021). The carbon sink capacity of moss tundra in Adventdalen is shown to decline in response to grubbing. This effect may be explained by repeated disturbance disrupting photosynthetic tissues and exposing the previously protected organic layer to erosion (Van Der Wal et al., 2007). Extrapolations reveal that carbon loss in response to grubbing may cover extensive areas across Svalbard (Speed et al., 2010b). Higher intensities of experimental grubbing are furthermore documented to cause decreases in plant diversity, something that appears to be less evident in wetter sites covered by thicker bryophyte layers. Bryophytes most likely increase the resilience of communities to disturbance by protection of rhizomes (Speed et al., 2010a). Evidently, grubbing has the potential to impact Arctic ecosystems at multiple levels. The responses appear to vary greatly across habitats (Petit Bon et al., 2021), but how any potential effect of grubbing on ALT would be influenced by variation in environmental factors is not known.

The valuable effect of a deep bryophyte layer on maintaining low soil tem-

peratures and permafrost stability in the face of climate change is widely recognized (Atchley et al., 2016; Grünberg et al., 2020; Soudzilovskaia et al., 2013), and grubbing is repeatedly demonstrated to disrupt bryophyte layers and influence plant communities (Gornall et al., 2009; Kotanen and Jefferies, 1997; Ravolainen et al., 2020; Speed et al., 2010a). However, whether the effect of grubbing may directly affect soil temperatures and ALT is still not explored. Thus, in this thesis, I will investigate how grubbing in combination with factors such as soil moisture and bryophyte and organic layer thickness affects soil temperature and ALT throughout a study period of one growing season.

1.5 Aims

This study is based on two hypotheses: 1) Simulated grubbing applied in early season will lead to an increase in soil temperature and ALT due to a disrupted bryophyte layer. 2) The effects of simulated grubbing on temperature and ALT will be stronger earlier in the growing season than later, and protection by a thicker insulating layer of bryophytes will mitigate the disturbance effect.

I tested these hypotheses at a High-Arctic polygon site in Adventdalen, Svalbard, a common feeding area for geese. I applied simulated grubbing in order to compare disturbed and undisturbed plots along gradients of contrasting vegetation, bryophyte layer thickness and soil moisture.

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Methods

2.1 Study site

The study site was situated in central Adventdalen, Svalbard (78°11'N 15°55'E, see map in Fig. 2.2), where data collection was carried out from 17th June (week 25) to 7th September (week 36) 2021. Adventdalen is a wide valley originating about 30 km inland and forming a 3.5 km wide river delta which runs into the Advent fjord. Above the river, banks of sediments and moss tundra cover most of the ground before reaching larger mountains consisting of sedimentary rock. The Arctic climate in Adventdalen is strongly influenced by the sea. Thus, even though the normal (1991-2020 average, Svalbard Airport) winter temperature is at -10 to -12°C, it has over the last decades become more common to encounter shorter time periods of temperatures above zero in winter (Peeters et al., 2019). In the winter of 2021, the lowest temperature was recorded at -24°C in March. The period of continuous snow cover usually begins in late autumn, peaks in April and lasts until the end of May. The snow layers measured at the Adventdalen weather station (See location in Fig. 2.2) vary between 10 and 35cm in depth at the deepest (2017-2022). The snow conditions are, however, strongly affected by wind and can be considerably deeper in some areas, depending on topography. The normal (1991-2020 average, Svalbard Airport) summer season temperatures are lowest in June with 3.6°C, and highest in July and August with 7.0 and 6.0°C, respectively. The precipitation is generally low, with a normal precipitation in June of 9 mm, 20 mm in July and 23 mm in August. In 2020, the snow cover season did not fully start until December and the snow cover lasted until the first week of June 2021. The 2021 summer

was colder than normal (1991-2020 average, Svalbard Airport), with an average temperature in July of 6.2°C (Fig. 2.1) at the Adventdalen weather station. Most of the summer was dry, with one day of 11mm rainfall 19th July, and some days with lighter rain (all climatic data are from MET Norway (The Norwegian Meteorological Institute)).

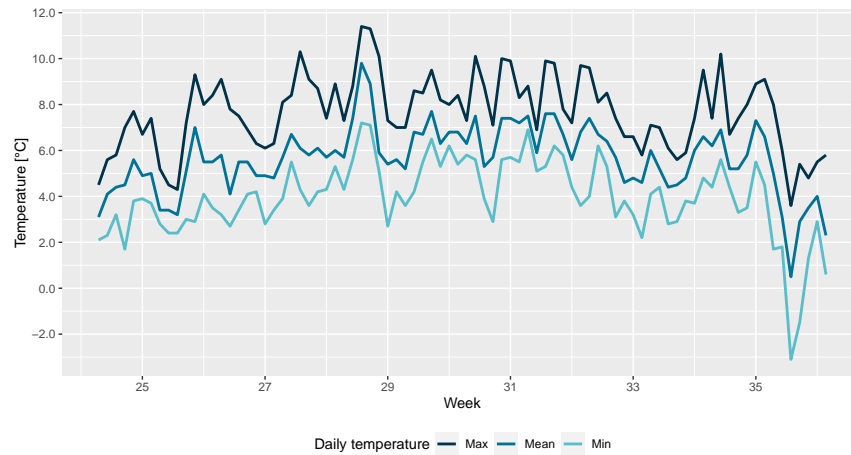


Figure 2.1: Daily minimum, maximum and mean air temperatures from the Adventdalen weather station covering the weeks of the study period (16th June to 7th September 2021).

Within the moss tundra, close to the riverbed, smaller areas of polygons formed by the periglacial landscape are located. The experiment was set up in one of these locations, dominated by low-centered ice-wedge polygons, formed as a result of expanding ground ice. The polygons measure about \varnothing 10-20 m, consist of a topographically lower centre encircled by a higher rim, and are delineated by ice-wedge troughs at the perimeter (see illustration in Fig. 2.2). Cracking and expansion as a result of cold events in early winter dynamically forms an ice-wedge in the trough. In spring and summer, the cracks are filled with meltwater which then again freezes in winter (Christiansen, 2005; Harry and Gozdzik, 1988; Matsuoka et al., 2018). The rims are often wind-affected with a shallow layer of snow and provide drier, nutrient-poor habitats dominated by vascular plants, transitioning into more wet, nutrient rich centres dominated by bryophytes (Zibulski et al., 2016). Here, snow tends to accumulate in winter and the water table is usually high from melt-water in early summer (Christiansen, 2005; Jorgenson et al., 2015; Watanabe et al., 2017). The considerable variation in conditions within each polygon allowed for investigating how variations in organic layer, bryophyte thickness and soil moisture affects soil temperature and ALT. Polygons are also common feeding grounds for geese (Beaulieu et al., 1996).

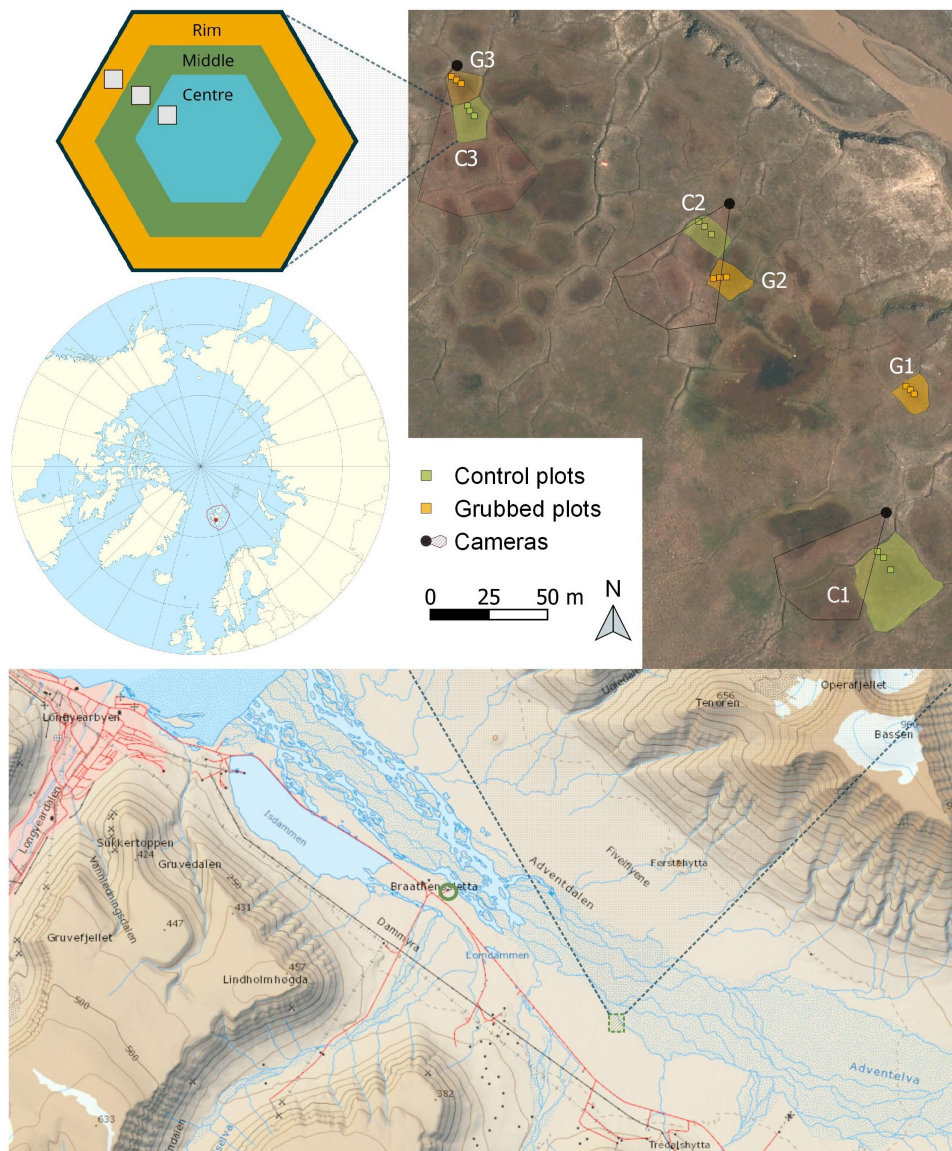


Figure 2.2: Map covering the study site in Adventdalen (lower), Svalbard (middle left). The location of Adventdalen weather station is indicated by a green circle, and the polygon site by a green square. The locations of the studied polygons and respective plots are visualized in the upper right aerial photograph. The grubbed polygons are displayed in orange, and the control polygons in green. The positions of the cameras and their approximate coverage are also indicated. An illustration of a simplified polygon (upper left corner) presents the rim, middle and centre parts and approximate positions of the plots within the polygon.

Adventdalen is a well known feeding site for pink-footed geese (*Anser brachyrhynchus*) during snowmelt (Anderson et al., 2012; Fox et al., 2006). The Svalbard

reindeer (*Rangifer tarandus platyrhynchus*) are also common grazers in the area (Pedersen et al., 2019; Staaland, 1984; Tyler et al., 2008), but the disturbance from these is less intense than that from geese (Van der Wal et al., 2020). Pink-footed geese are documented to prefer to grub in or close to wet habitats, which is also where most of their preferred forage species are found (Anderson et al., 2012; Speed et al., 2009).

2.2 Data collection

With the aim to find suitable areas in proximity to each other, six polygons were selected. Among three of the polygons, plots were already established for long-term monitoring. These were used as control plots. Three additional polygons were selected based on similarity to the original plots in size, microtopography, soil moisture and vegetation composition. The area is a common research site, causing several polygons to already be in use and thus exposed to preceding disturbances. There were therefore a limited number of suitable polygons available, and some plots consequently deviate from the criteria the selection was based on. I also tried to avoid excessive disturbance to the polygons and did not establish new control plots.

The rim was the highest point within a given polygon, showed driest condition and was dominated by vascular plants such as *Salix polaris*, *Bistorta vivipara*, *Equisetum arvense ssp. alpestre*, *Dupontia fisheri* and *Alopecurus ovatus*, and less by bryophytes. The middle plot was moist and dominated by *Polytrichum* spp., in addition to *Aulacomium* spp. and a smaller cover of vascular plants than that seen in the rim. The centre was wet and dominated by bryophytes of the family Amblystegiaceae in addition to shoots of *Carex subspatheacea*. In early season, the centre plots were submerged in about 50 cm of water which dried out over the summer.

Within each polygon, three plots were positioned. The plots selected for grubbing treatment were placed in the same overall position as the already established control plots, on a line in an approximately north-west direction from the centre to the rim of each polygon (see illustration in Fig. 2.2). One plot was placed at the rim, one in the middle and one in the central part. The control polygons were named C1, C2 and C3, and the polygons with grubbed plots G4, G5 and G6 (Fig. 2.2). The plots measured 50x50 cm and were all placed with one side facing north. All measurements were done standing on the side facing south. The control samples were taken just outside of the control plot, in the northern and eastern side, thus minimizing disturbance on the plot itself. The measurements on the disturbed plots were taken inside the plot, close to its centre, to record the maximum extent of the grubbing effect.

In order to investigate the effect of disturbance from goose grubbing in a controlled manner, grubbing was simulated manually (Fig. 2.3). The grubbing treatment was applied on 17th and 18th June, using a $\varnothing 2$ cm tube pressed 5 cm into the ground and twisted, similarly to the method used by Speed et al. (2010a). Pipes of steel or solid plastic were used. Where the soil was too sturdy or the moss layer too thick for the pipe to cut properly through, a hammer was used to increase the force by which the grubbing was applied, thus forming holes into the ground.

The simulated grubbing was applied to approximately 50 % of the plot, estimated by keeping the plot covered by a 50 cm x 50 cm quadrat with 5x5 squares while applying the grubbing. The pipe was pushed down to form holes in a similar pattern within each square of the quadrat, so that the final overall disturbance covered a total of 50 % of the plot area. In order to ensure that the entire plot, including the edges, would be affected by the grubbing to similar extents, the treatment was extended 10cm beyond the plots. Chunks of soil and moss pulled out of the ground as a result of the simulated grubbing were left on top of the plot, similar to natural grubbing by geese (personal communication with Eeva Soininen, Simone Lang and Virve Ravolainen). Areas with vegetation affected in the same manner were also seen in the area surrounding the polygon site (Fig. 2.5).

The plots in the polygon centres were still covered in water at the time when simulated grubbing was applied, obscuring the view of the ground, thus challenging the procedure (see photos in Fig. 2.4). In order to evaluate the similarity of the final extent of simulated grubbing in each plot, the total percentage cover of holes was estimated at the mid season when all plots were dried out, allowing for a more accurate comparison. At this point, the holes appeared to decrease in diameter as the surrounding bryophyte layer expanded into them. On average, the holes covered about 40 % of the grubbed plots at mid season. In the centre plots, a major part of the moss had been torn from the turf and was laying loose on top of the ground, covering the holes.

The microtopography from rim to centre within each polygon was measured in the beginning of the season in order to investigate how belowground ALT and its development follows the topographical variations above. This was done by placing a rope horizontally between the rim and centre plot and recording the vertical distance from the rope to the ground at intervals of 50 cm along the rope. The microtopography relative to the highest point measured in each polygon was then calculated. ALT was measured monthly (29th June, 27th July and 24th August), also this at 50 cm intervals from rim to centre. As the central parts of the polygons were more homogeneous than the outer parts, the interval was altered to 1m when reaching the centre if the distance between the middle and centre plots was ≥ 4 m.

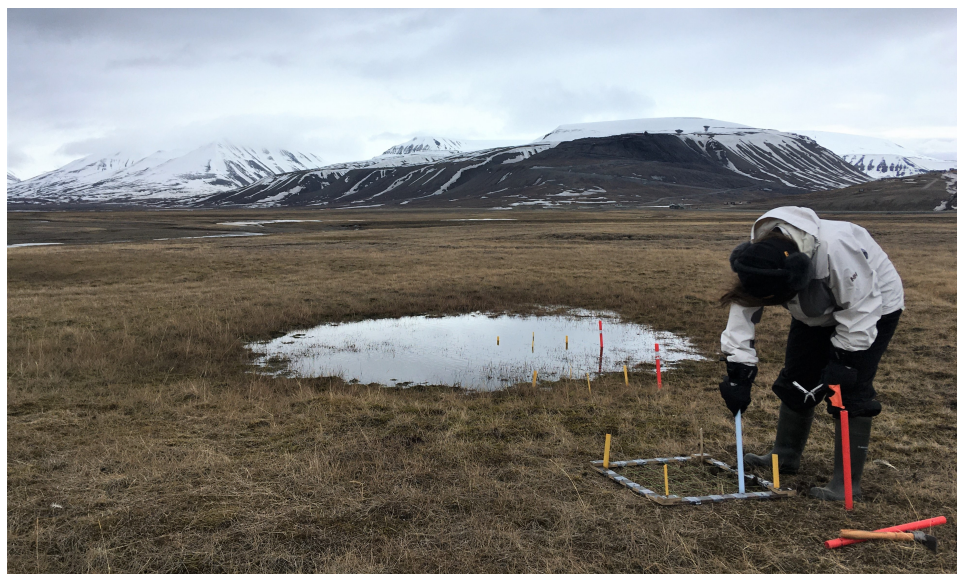
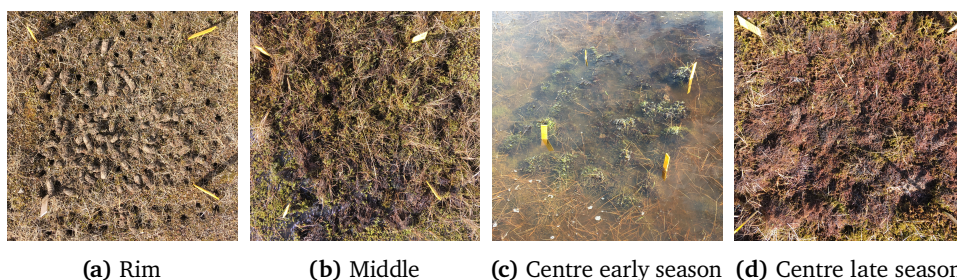


Figure 2.3: Application of simulated grubbing treatment in the rim of polygon G1.



(a) Rim

(b) Middle

(c) Centre early season

(d) Centre late season

Figure 2.4: Photographs of the plots in polygon G1 after application of simulated grubbing.

After applying the simulated grubbing, temperature loggers (Gemini Tinytag Plus 2 - TGP-4020 for the rim and middle plots, Gemini Tinytag Aquatic 2 TG-1400 for centre plots) were installed in each plot in order to monitor the daily variations in soil temperature over the season. The loggers were placed to record the temperature at about 15 cm within the south-west corner of the plot at a depth of approximately 5 cm, measuring every hour over the study season, from 18th June to 7th September.

Measurements of active layer thickness, soil temperature and soil moisture were carried out in each plot at weekly intervals from 23rd June (week 25) to 7th September (week 36) to investigate any relation to simulated grubbing over time. Hereafter, these measurements will be referred to as point measurements. Due to practical constraints, the measurements in week 35 were postponed for three days.



Figure 2.5: Examples of locations exposed natural grubbing in the area surrounding the study site.

Active layer thickness (ALT) was measured using a $\varnothing 10$ mm, 1.5 m long metal probe pushed vertically into the ground until it reached the ice layer. This was done twice per plot.

Soil moisture and soil temperature were sampled using digital handheld meters (ML3 ThetaKit DeltaT and Ebro TFX 410 Precision core thermometer, respectively). As soil moisture level is known to vary considerably within smaller areas, three measurements were done in different parts of the plot. Where the water level was too high for the soil moisture meter to take any samples, the soil moisture was registered as 100 %. The soil temperature was more stable and measured twice within each plot at a depth of approximately 10 cm. The plots in the polygon centres were covered by a high water table the first 1-2 weeks. This prevented soil temperature measurements by the handheld meters, as these were not impervious to water.

To test whether there were any effects of plot size, and thus an edge effect, on ALT in the grubbed plots, ALT transects were conducted at monthly intervals (29th June, 27th July and 24th August). ALT was sampled starting within the grubbed plot centre, then towards the edge of the plot towards north-east and extending 10cm, 20cm, 30cm, 40cm, 60cm, 80cm and 100cm beyond the plot.

In order to identify how the temperature changed with depth, the soil temperature was sampled using a temperature probe (Greisinger SoilTemp 1700) at depth intervals of 5 cm until reaching the ice layer. The measurements were done in each plot to investigate any variation in vertical rate of change in soil temperature between grubbed and control plots. The probe arrived in July,

and these measurements were done on 27th July and 24th August.

Organic and moss layer thickness were recorded in order to detect its potential influence on ALT. They were measured by cutting a square of approximately 15 x 15 cm out of the soil 0.5 m north-east of each plot in an area with a species composition similar to that in the plot. The thickness of two layers; the top layer, including live and dead moss, and the organic layer beneath were measured at all four sides of the soil square. The average thickness of each layer in each plot was subsequently calculated. For some plots, the layers were partly mixed together, making the distinction between them ambiguous. In these cases an approximation had to be made. As the thickness of the organic and moss layers showed a linear positive correlation (See appendix, Fig. 5.1), they were combined into a single variable, the organic layer thickness (OLT) and analyzed accordingly.

The percentage cover of green and senescing vascular plants was estimated weekly, covering the plot with a 50 cm x 50 cm quadrat frame with 10x10 squares with sides of 5 cm. The estimations were done by the same person for the main part of the season, except for week 31, 32 and 33 where another person stepped in.

In order to examine the similarity in vegetation composition in each position among the plots, the composition of vascular plant and bryophytes in each plot was recorded at the peak growing season in the end of July (19th July to 23rd July 2021). This was estimated using a 50 cm x 50 cm quadrat frame with 5x5 squares, where the presence and absence of plant species present in the plot was recorded in each square (Ståhl et al., 2020). As the focus on this study is on the physical role of the vegetation on soil conditions, the recorded species were allocated into functional groups (Table 2.1) based on the groups of vascular plants defined by Elmendorf et al. (2012) and bryophytes by Lett et al. (2021). Horsetails and foliose lichen were left as separate groups. Biological soil crust, a composition of microorganisms and soil particles that form on the ground and was present in one plot (Williams et al., 2017), was grouped as crust.

The presence of herbivores in the area was monitored, as any large populations in the vicinity of the plots during the study period could cause disturbance to the measurements. Three cameras were put up at the site in the beginning of the season, taking photographs of the area every 20 minutes (see placements in Fig. 2.2). The photos were examined for presence of geese, and daily counts were done. Additionally, the number of reindeer and geese present at the site were registered every week upon arrival.

Table 2.1: Allocation of vascular plant species, bryophytes and lichen into functional groups. Due to complexity in determining bryophytes and lichen to species, some were classified to higher taxonomic ranks.

Functional group	Vascular plant species
Deciduous shrubs	<i>Salix polaris</i>
Forbs	<i>Bistorta vivipara</i>
	<i>Pedicularis hirsuta</i>
Grasses	<i>Alopecurus ovatus</i>
	<i>Calamagrostis neglecta</i>
	<i>Dupontia fisheri</i>
Horsetails	<i>Equisetum arvense</i> ssp. <i>alpestre</i>
Rushes	<i>Luzula confusa</i>
Sedges	<i>Carex subspathacea</i>
Bryophytes	
Branched turf (BT)	Amblystegiaceae
	<i>Tomentypnum nitens</i>
	<i>Sanionia uncinata</i>
Leafy liverworts (LL)	Jungermanniales
Polytrichales (Po)	<i>Polytrichum</i> spp.
Short unbranched turf (SU)	<i>Aulacomnium</i> spp.
	<i>Pohlia</i> spp.
	<i>Dicranum</i> spp.
Sphagnum (Sp)	<i>Sphagnum</i> spp.
Lichen	
Foliose lichen	<i>Peltigera</i> spp.

2.3 Data analysis

The data analysis was done in R version 4.0.3. In order to investigate the effect of simulated grubbing on soil temperature and ALT, data were explored visually. The patterns observed in the graphs were used to determine which explanatory and response variables to use in linear mixed effects models and linear models in order to investigate the relationships between these variables.

The vegetation composition in each plot was compared by summing the functional group presence and absence counts (see appendix, Table 5.1), which were then used to produce a PCA (Principal Component Analysis) biplot. In order to account for the high number of zero values, the data were log-transformed after adding a constant of 1 to all counts (Kenkel, 2006) before running the PCA using the function *prcomp* in base R. As all values were in counts, the PCA was based on a covariance matrix (Kenkel, 2006).

In order to investigate the effect of grubbing on soil temperature and ALT, linear mixed effects models based on the point measurements of soil temperature, soil moisture and ALT from single weeks in early season (week 25), mid season

(week 30, peak of vascular plant cover, Fig. 3.3) and late season (week 36) were used (Table 2.2 a and b). The response variables were point measurements of temperature and ALT, which were explained by the fixed variables soil moisture and the interaction grubbing treatment x OLT. Plot identity was added as a random effect as there were multiple measurements in each plot.

Furthermore, the hourly logged temperatures were used to explore the effect of grubbing on daily temperature variation, which has been shown to dependent on bryophyte layer thickness (Soudzilovskaia et al., 2013; Gornall et al., 2007). In these models (Table 2.2c), I used the mean daily temperature amplitude as response variable and the same fixed variables as for the linear mixed effects models above; soil moisture and grubbing treatment x OLT. As there was only one response variable calculated for each plot, plot identity could not be included as a random variable, and linear models were used. I constructed four models; one model for the time period from the start of the measurements to the time of peak temperature (18th June - 8th August 2021), and the time periods for the three other models corresponded to the same weeks as those used for the linear mixed effects models (i.e. weeks 25, 30, and 36, see above).

Table 2.2: Structure of linear mixed effects models on (a) soil temperature, (b) active layer thickness ALT and (c) linear model on soil temperature amplitude.

Linear mixed effects models	
(a)	Temperature ~ Soil moisture + Treatment * OLT + (1 Plot)
(b)	ALT ~ Soil moisture + Treatment * OLT + (1 Plot)
Linear model	
(c)	Mean daily temperature amplitude ~ Soil moisture + Treatment * OLT

/ 3

Results

3.1 Description of measured variables

The measured variables; polygon topography, vegetation composition, OLT, soil temperature and ALT, are visualized to display general trends in the data. They demonstrate differences between the polygons, variation in the environmental conditions within them and how these are related to the simulated grubbing. The variables used in the models are based on this exploration.

The studied polygons generally had the highest point at the rim, with topography decreasing in elevation towards the plot positioned in the centre. The difference in relative topography between rim and centre varied between the polygons; the centre plots in polygon C1 and G1 were about 20 cm lower than the highest point, while the centres in polygons C2 and G2 were barely lower than their rims (Fig. 3.1). The middle plots were generally positioned topographically between the rim and centre plots, though in polygon C2 and G2, the middle plot was at the same relative height as centre and rim, respectively. The troughs were generally deeper than the centre plots (Fig. 3.1), varying from a depth of 16 cm to 32 cm. Polygon G1 diverged from this by having a trough depth at 5 cm, distinctly less deep than the 19 cm deep centre plot.

The polygons showed some variations in size, where the distance from the rim to centre plot varied from about 5 m in polygon C3, G1, G2 and G3, to reaching close to 10 m in polygon C1 and C2 (Fig. 3.1). ALT followed the ground microtopography by having a stable depth relative to the surface across all polygons. The deepening from early (week 26) to mid season (week 30) was generally larger than that occurring from mid to late season (week 34) (Fig. 3.1).

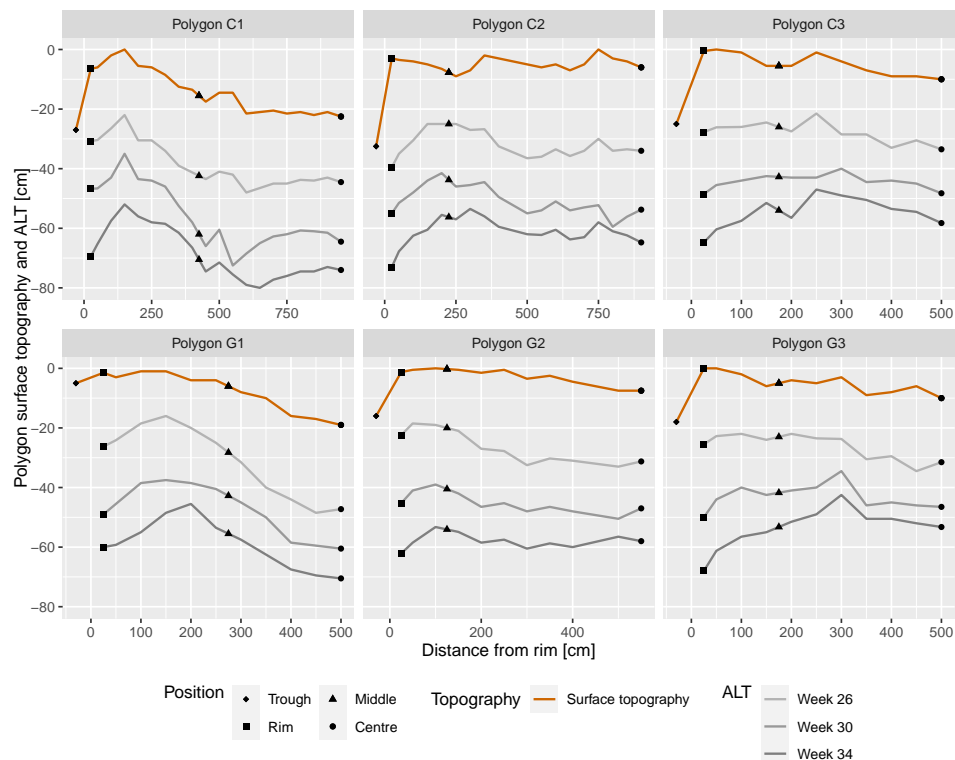


Figure 3.1: Relative surface topography of each polygon as a transect at fixed distances from trough to the rim, middle and centre plots. The topographically highest point in each polygon was set to a depth of zero, and the other topographical recordings of that polygon calculated relative to this height. Active layer thickness (ALT) is shown for early (week 26), mid (week 30) and late (week 34) season, relative to the topography.

Plant functional group composition differed between plots in the centre of the polygons and those in the middle and the rim (Fig. 3.2). In contrast, middle and centre plots differed from the rim plots in percentage cover of vascular plants. The vascular plant cover was higher in the rim compared to the middle and centre plots (Fig. 3.3). The centre plots were thus defined by a dominating cover of SU bryophytes and sedges, the middle by presence of vascular plants but still a substantial cover of bryophytes, and the rim by a dominating cover of vascular plants compared to bryophytes.

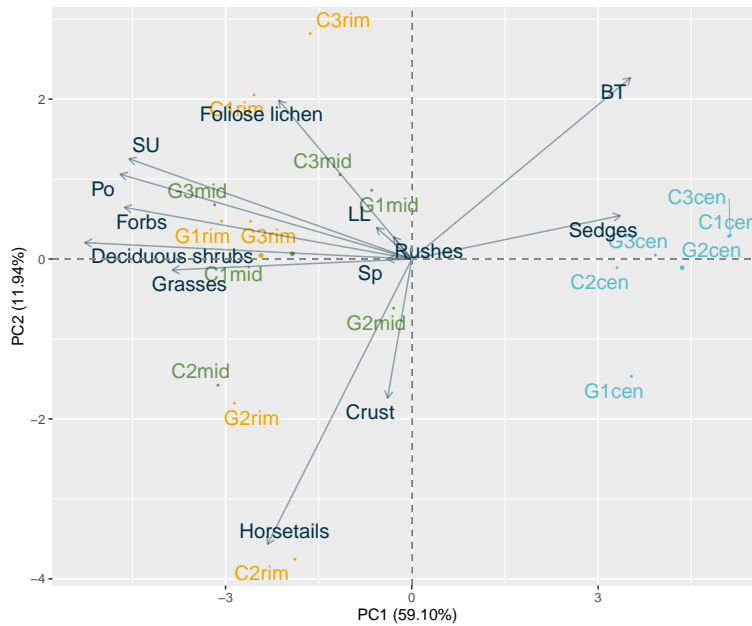


Figure 3.2: PCA biplot based on counts of presence of vascular plant, bryophyte and lichen functional groups, and crust, in each plot. The bryophyte functional groups are shortened to BT (Branched turf), LL (Leafy liverworts), Po (Polytrichales), Sp (Sphagnum) and SU (Short unbranched turf). Plots positioned at the rim, middle and centre are coloured yellow, green and blue, respectively. The percentage fraction of variation described by each axis is in parentheses.

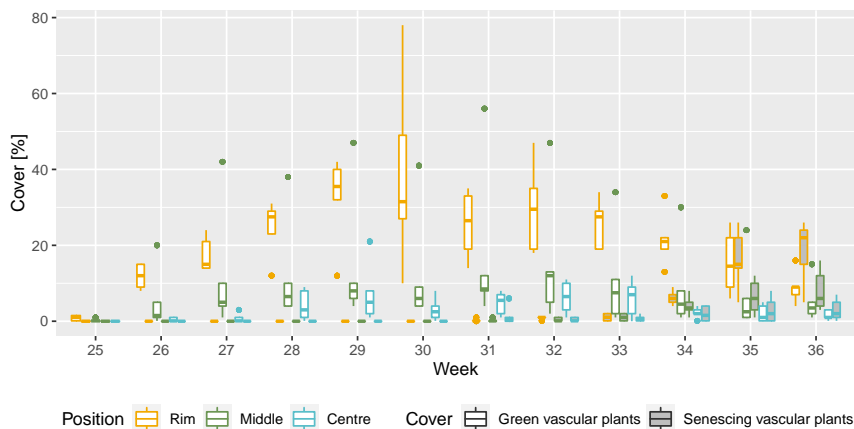


Figure 3.3: Percentage cover of green (white boxes) and senescing (grey boxes) vascular plants from week 25 to 36, 2021, in rim (yellow), middle (green) and centre (blue) plots. The boxes represent the interquartile range (IQR) with the median indicated by a horizontal line. The whiskers span up to 1.5 x IQR vertically from each box, and outliers are represented by points.

The OLT, soil moisture, soil temperature and ALT were correlated to different extents over the season (see Fig. 3.4 for all comparisons and reference to Pearson correlation coefficients in this paragraph). The division into early, mid and late season were determined based on Adventdalen weather station air temperatures (Fig. 2.1), which respectively had a general increase in week 25-28, was more stable in week 29-34 and fell in week 35-36. In early season, when the water level was high in the bryophyte-rich polygon centre, OLT had a strong, positive correlation with soil moisture (0.519, $p < 0.001$). The strength of the correlation decreased later in the season. The correlation of OLT with soil temperature and ALT was negative. For soil temperature the correlation with OLT was stronger in mid season (-0.409, $p < 0.001$) when temperatures were higher, and for ALT later in the season (-0.643, $p < 0.001$) when ALT was deeper. Soil moisture showed no general correlation with soil temperature nor ALT, even though there was some negative correlation with ALT in mid season (-0.302, $p < 0.001$). Soil temperature and ALT were positively correlated all season, though more strongly in earlier (0.868, $p < 0.001$) compared to mid (0.479, $p < 0.001$) and late season (0.480, $p < 0.001$).

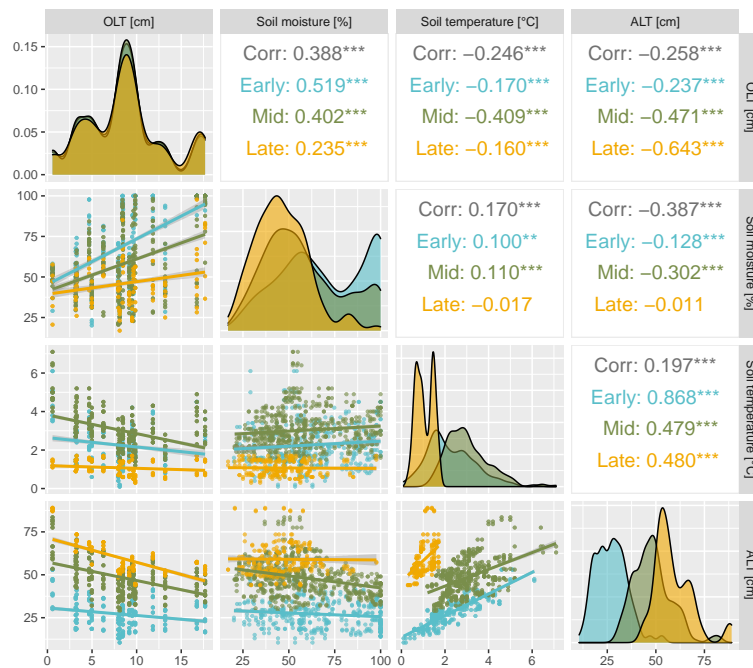


Figure 3.4: Lower panels: scatter plots of organic and bryophyte layer thickness (OLT), soil moisture, soil temperature and active layer thickness (ALT) for early (week 25-28), mid (week 29-34) and late (week 35-36) season. Linear regressions are drawn as trend lines, with 95% confidence intervals presented in grey. Upper panels: overall and seasonal Pearson correlation coefficients (*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$). Diagonally: data distributions.

There were no clear differences between grubbed and control plots in soil temperature and ALT among the rim and middle plots (3.5c and d), but soil temperature in the centre control plots appeared to increase more compared to the grubbed plots earlier in the season (3.5c). The same control plots showed a deeper OLT compared to that of the grubbed plots (3.5a). The daily temperature amplitude in the centre plots (Fig. 3.6) was about 0.5-1 °C lower compared to the grubbed plots early and late in the season (Fig. 3.6). The plots in the rim had a more shallow OLT (3.5a), in addition to higher soil temperatures and deeper ALT compared to the middle and centre plots (3.5). There were no general trends in soil moisture when comparing grubbed and control plots (3.5b).

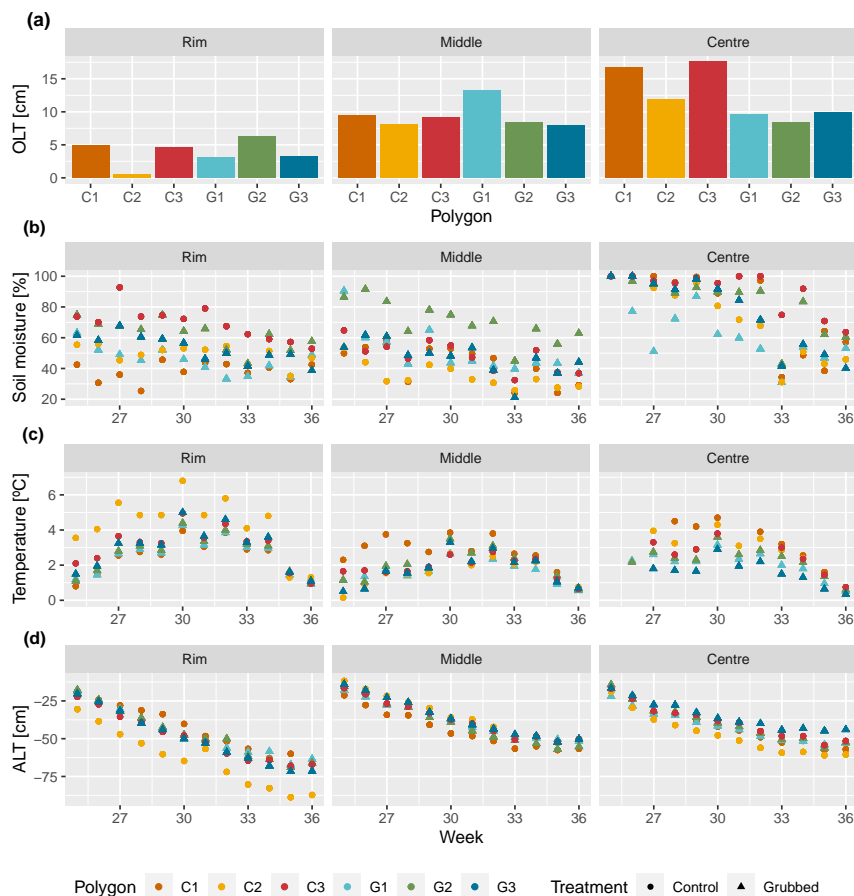


Figure 3.5: Overview of plot measurements of (a) organic and bryophyte layer thickness (OLT), and weekly point measurements of (b) soil moisture, (c) temperature and (d) active layer thickness (ALT) over the season. The data are presented for each polygon and divided into rim, middle and centre plots. Control plots are indicated by points, and grubbed plots by triangles.

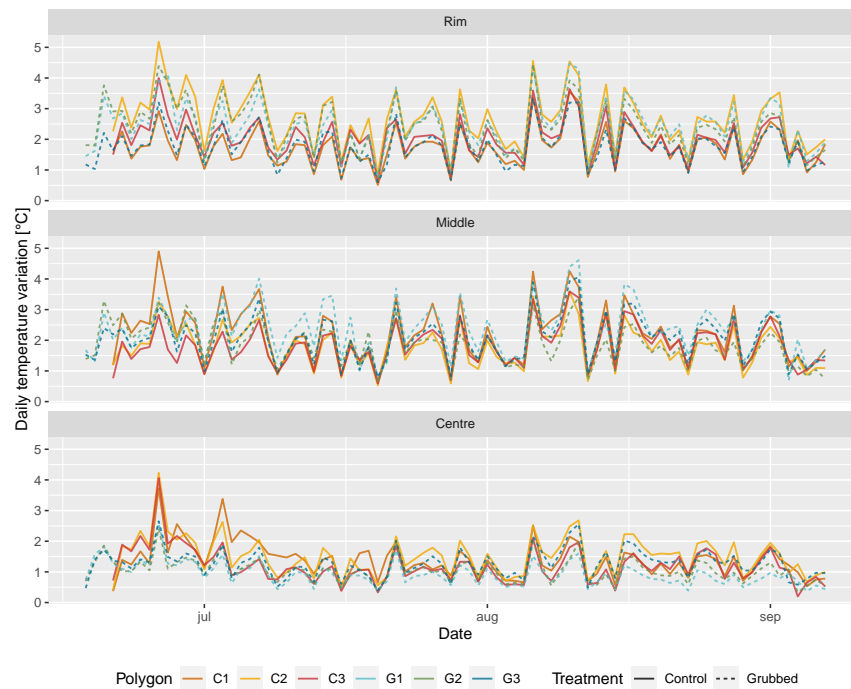


Figure 3.6: Daily temperature amplitude for each polygon over the season, divided into rim, middle and centre plots. Lines representing grubbed plots are dashed.

From observations in the time-lapse photos taken at the site, groups of geese were present in a large, wet polygon bordering the north-west side of polygon C1 two days during early season. There was a group of 8 barnacle geese and 2 pink-footed geese 3rd July (week 26), and a larger group of 57 barnacle geese at the same spot 14th July (week 28). The group of barnacle geese appeared to stay within a limited area and none were observed in the photos from the cameras covering the other polygons. Two pink-footed geese were observed in the polygon north of polygon C2 27th June and in the polygon south of polygon C3 21st August. There were no traces of recent grubbing in any of the control plots.

Additionally, from personal observations at the site, there was a group of approximately 30-50 pink-footed geese observed at the same spot referred to above, bordering polygon C1, in early June. These were observed prior to when the cameras were set up, and I did not make any personal observations of geese at the site during implementation of the measurements. Based on counts of reindeer present in the area surrounding the polygons at the time of weekly arrival to the site, more reindeer were observed earlier than later in the season. A daily average of 6 reindeer was calculated for early season (week 25-28), 0.8 for mid season (week 29-34) and 0.5 for late season (week 35-36).

3.2 Impacts of simulated grubbing treatment on temperature and ALT

As presented in the outputs from the linear mixed effects models and linear models in Table 3.1, the simulated grubbing was neither shown to have a significant effect on soil temperature, ALT nor on daily soil temperature amplitude over the season. The lack of effect of grubbing was also observed in the transect measurements of ALT (see appendix, Fig. 5.4) and depth of soil temperature (see appendix, Fig. 5.3), measured at monthly intervals. Though not significant, there was a general trend of negative effect of simulated grubbing on ALT (Table 3.1b) in all seasons, but stronger in the first week (-5.51, [-14.04, 3.02]). A negative effect of grubbing indicates a lower soil temperature and less deep ALT in the grubbed plots, while a positive effect would indicate higher soil temperatures and deeper ALT. The magnitude of grubbing effect was larger in early season for temperature, also showing a negative effect (-1.61 [-3.73, 0.51], Table 3.1a). Later in the season, the effects on point soil temperature were positive, but the magnitudes lower (Table 3.1a). The daily temperature amplitude demonstrated a low negative effect of grubbing across all season, though it was here less strong in early (0.05 [-1.36, 1.46]) than in mid and late season (-0.13 [-1.15, 0.90] and -0.15 [-0.98, 0.67], Table 3.1c).

The interaction simulated grubbing x OLT was not significant for any of the variables in the explored weeks (Table 3.1), and there did not appear to be any general trend in these numbers. OLT had some significant negative impact on soil temperature, soil amplitude and ALT. This effect was significant for ALT all season (Table 3.1b), but only in late season for soil temperature (Table 3.1a) and temperature amplitude (Table 3.1c). Soil moisture did not have impact on any of the explored variables throughout the season (Table 3.1), and the confidence intervals did not indicate any notable variation in these results.

The plot identity described 95-97 % of the variance in all but one of the linear mixed effects models (Table 3.1a and b). In the late season model on soil temperature (Table 3.1a), plot identity described 73 % of the variance. The adjusted R squared from the linear model on temperature amplitude reflected a low (0.08) part of the variance explained by the model in early season (Table 3.1c), while it was moderately higher (0.21-0.36) in mid, late, and for early season until maximum temperature.

Table 3.1: Results from linear mixed effects models of simulated grubbing effect on (a) point soil temperature and (b) active layer thickness (ALT) from single weeks in early (week 25), mid (week 30) and late (week 36) season. Fixed effects are presented as °C for temperatures, and cm for ALT. Random effects are presented as standard deviations, and the percentage of variance explained by plot identity is in parentheses. (c) Results on plot mean daily temperature amplitudes for single weeks in early (week 25), mid (week 30) and late (week 36) season, and until reach of maximum temperature (week 25-31). The adjusted R squared is presented for each linear model. Confidence intervals (CI, 95%) are presented in brackets for all effect sizes, and those not including zero are in bold. N (Plot) indicates the number of analyzed plots in each model.

(a) Soil point temperature

	Early season [95 % CI]	Mid season [95 % CI]	Late season [95 % CI]
Fixed effects			
Intercept	2.90 [1.42, 4.39]	4.98 [3.77, 6.19]	1.13 [0.92, 1.34]
Soil moisture	0.00 [-0.00, 0.00]	0.00 [-0.00, 0.01]	0.00 [-0.00, 0.00]
Grubbing	-1.61 [-3.73, 0.51]	0.34 [-1.69, 2.37]	0.05 [-0.30, 0.39]
OLT	-0.19 [-0.40, 0.03]	-0.09 [-0.21, 0.02]	-0.03 [-0.05, -0.01]
Grubbing:OLT	0.16 [-0.13, 0.45]	-0.13 [-0.36, 0.10]	-0.03 [-0.07, 0.01]
Random effects			
Plot	0.83 (96%)	0.90 (95%)	0.15 (73%)
Residual	0.18	0.21	0.09
N (Plot)	12	18	18

(b) ALT

	Early season [95 % CI]	Mid season [95 % CI]	Late season [95 % CI]
Fixed effects			
Intercept	24.01 [18.95, 29.07]	52.78 [44.96, 60.60]	74.34 [64.52, 84.17]
Soil moisture	0.00 [-0.01, 0.02]	0.00 [-0.03, 0.03]	0.00 [-0.02, 0.02]
Grubbing	-5.51 [-14.04, 3.02]	-0.31 [-13.48, 12.86]	-1.10 [-17.76, 15.56]
OLT	-0.50 [-0.98, -0.03]	-0.91 [-1.64, -0.18]	-1.49 [-2.41, -0.57]
Grubbing:OLT	0.35 [-0.60, 1.30]	-0.50 [-1.96, 0.97]	-0.67 [-2.53, 1.18]
Random effects			
Plot	3.80 (97%)	5.86 (96%)	7.42 (97%)
Residual	0.71	1.13	1.24
N (Plot)	18	18	18

(c) Soil temperature amplitude

	Early season [95 % CI]	Mid season [95 % CI]	Late season [95 % CI]	Until max. temp [95 % CI]
Intercept	3.17 [1.96, 4.38]	2.88 [2.09, 3.66]	2.21 [1.44, 2.97]	2.82 [1.96, 3.67]
Soil moisture	-0.01 [-0.03, 0.01]	-0.01 [-0.03, 0.00]	-0.01 [-0.03, 0.01]	-0.01 [-0.03, 0.00]
Grubbing	0.05 [-1.36, 1.46]	-0.13 [-1.15, 0.90]	-0.15 [-0.98, 0.67]	-0.09 [-1.23, 1.06]
OLT	-0.04 [-0.14, 0.07]	-0.03 [-0.10, 0.03]	-0.05 [-0.10, -0.01]	-0.03 [-0.11, -0.04]
Grubbing:OLT	-0.01 [-0.17, 0.15]	0.01 [-0.10, 0.13]	0.01 [-0.08, 0.10]	0.01 [-0.12, 0.13]
Adjusted R ²	0.08	0.34	0.36	0.21
N (Plot)	18	18	18	18

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Discussion

The application of simulated grubbing was not observed to have any significant effect on soil temperature, daily temperature amplitude, nor ALT. Though not significant, there were indications that the magnitude of grubbing effect was stronger in early than mid and late season. As expected, plots with thicker organic and bryophyte layers generally had lower soil temperatures, temperature amplitudes and more shallow ALT than those with more shallow OLT, but no interaction of OLT with simulated grubbing was found.

4.1 Effect of simulated grubbing and impact of covariates

The absence of any clear impact of simulated grubbing on ALT may reflect that the disturbance of the bryophyte layer from the simulated grubbing was too weak to influence the stability of the extensive permafrost layer in this area. Additionally, this study was carried out over one season, thus only presenting the short-term effects of grubbing. Grubbing is a disturbance happening continually over decades, causing changes in vegetation composition (Ravolainen et al., 2020; Speed et al., 2010a). The long-term effects of simulated grubbing applied yearly might therefore reveal a different response in ALT. Moreover, there is spatial variation in the distribution of ground ice content within the terrain of Adventdalen, causing considerable small-scale variation in ALT depending on

local ground sediments (Cable et al., 2018). In this study, each plot covered 0.5 m², while grubbed areas in Svalbard may cover several square meters (Van der Wal et al., 2020). Plant diversity in smaller areas of disturbance and edges of disturbed sites is documented to be more resilient to simulated grubbing (Speed et al., 2010a), an effect which may also apply to soil temperature. Applying simulated grubbing to larger areas by the method used in this study would be tedious and cause extensive disturbance to already vulnerable ecosystems. In order to investigate whether large-scale grubbing affects soil temperature and permafrost, observational studies or long-term enclosure experiments by larger naturally grubbed areas may be more suitable.

The intensity of simulated disturbance applied to each plot was small compared to the degree of disturbance that can be seen in some naturally grubbed areas. The method of applying disturbance was based on that described by Speed et al. (2010a) and Petit Bon et al. (2021), covering about 50 % of the plot. They documented this intensity of simulated grubbing to have an impact on plant diversity (Speed et al., 2010a), and C and N contents of vascular plants (Petit Bon et al., 2021), respectively. Nevertheless, natural grubbing has the potential to entirely remove vegetation from large areas (Kotanen and Jefferies, 1997). Applying disturbance of a higher intensity is therefore likely to give a more representative simulation of grubbing, and might cause a more evident effect on soil temperature and, consequently, ALT.

Despite not being statistically significant, there was an unexpected pattern of lower soil temperatures, lower daily temperature amplitudes, and more shallow ALT in the disturbed plots. The method used for applying grubbing could provide an explanation for this apparent cooling effect of simulated grubbing. The bryophytes pulled out of the ground in the disturbed plots were not removed from the surface, and though physically disrupted may still have functioned as insulation when left on top of the ground. The heating effect expected as a result of the holes produced may therefore have been evened out by the cover of an effectively thicker bryophyte layer. A long-term experiment may provide different results, as the mosses left on top of the plots are likely to die and continual grubbing over several years may not provide opportunity for the vegetation to recover (Kotanen and Jefferies, 1997).

As no significant effect of simulated grubbing was found, whether the effect would vary over the season is also not known. However, the magnitude of the effect sizes for soil temperature and ALT were larger in early compared to mid and late season. This could indicate that soil temperature and ALT are more sensitive to environmental conditions earlier in the season, reflecting their larger spatial variation in early season (Grünberg et al., 2020). The temperature amplitude did on the other hand not appear to vary greatly over the season, and here, the lowest effect size was found in early season. As the

effect of grubbing on permafrost is a topic where the knowledge base is still low, the seasonal variations related to it require more investigation.

If any variation in temperature and ALT was to be recorded in response to simulated grubbing, what magnitude of effect to expect is unknown. Most experiments on the impact of grubbing examine effects on vegetation, species composition and erosion (Gornall et al., 2009; Jasmin et al., 2008; Jefferies and Rockwell, 2002; Speed et al., 2010a; Van der Wal, 2006). There are indications that trampling by large herbivores in winter diminishes the insulating capacity of snow, thus improving the permafrost stability (Beer et al., 2020), but the knowledge on direct effects of vegetation disturbance by herbivores on soil temperature and ALT is very limited. Despite a broad acknowledgement of the insulating effect of bryophytes on soil temperature (Atchley et al., 2016; Gornall et al., 2007; Grünberg et al., 2020; Soudzilovskaia et al., 2013), and repeated evidence for changes in vegetation and bryophyte cover in response to grubbing (Ravolainen et al., 2020), the link between grubbing and how it affects permafrost remains unclear.

Soil moisture did not appear to have any effect on soil temperature, nor on ALT. The lack of registered effect is presumably due to the dependency of soil moisture on the ice body which forms below ground (Clayton et al., 2021). This ground ice, which potentially develops over winter, again depends on a combination of soil water content, winter air temperatures and insulation from snow and organic layers (Atchley et al., 2016; Mackay and MacKay, 1974). Winter time processes and snowmelt timing are therefore influential on ALT development (Grünberg et al., 2020).

Due to the high heat capacity of water, wet soil requires more heat to thaw during summer compared to drier soils, contributing to a more stable ALT (Clayton et al., 2021). The polygons studied here had a high water table for a large part of the summer, provided by meltwater from snow accumulated in the lower parts of the polygons during winter (Christiansen, 2005). As the ice that forms in the ground influences ALT in combination with soil hydrology (Clayton et al., 2021), measuring soil moisture separately might not provide a complete picture of the processes determining ALT. Therefore, more extensive registrations over the whole year would be required to form a more thorough analysis of the processes taking place. Goose grubbing is also at its most intense during the time of snowmelt (Anderson et al., 2012), and applying simulated grubbing earlier might therefore have enhanced the accuracy of the disturbance effect.

4.2 Limitations of study and recommendations for future research

The polygon microtopography reflected overall similarity between the polygon structure and the allocation of plots positioned in the rim, middle and centre parts. Some of the natural variation among the plots is evident in the rim in polygon C2, which clearly diverges from the other plots in having a thin OLT. Consequently, the soil temperature and ALT in this plot is respectively higher and deeper than that observed in the other the rim plots. The variance seen in the model results was predominantly explained by plot identity, while the residual variance was negligible. In order to account for more of the variation between the plots, future studies could benefit from structuring a model where position is included as a random variable, and the plots nested within each polygon. This would require a study design with both control and grubbed plots within each polygon position. Here, minimizing excessive disturbance on the control polygons was prioritized.

Based on a combination of the data on presence and absence of functional groups and estimation of vascular plant cover, the plots in each position were shown to be similar in relative vegetation composition. In future research, applying the point intercept method will likely improve the accuracy of the representation of vegetation cover. This method also limits the subjective bias seen in cover estimations (Godínez-Alvarez et al., 2009). However, details on vegetation composition were not the focus of this study and a more efficient method was applied.

Vegetation is in some ecosystems documented to influence ALT (Wilcox et al., 2019). In summer, it may cool the ground by providing shade from direct sunlight (Way and Lapalme, 2021). However, in winter, taller vegetation such as shrubs may increase the effective snow depth by trapping snow, thus locally increasing the ground insulation. The insulating effect of deeper snow appears to have a stronger influence on ALT than that of summer shading, emphasizing the importance of winter conditions on ALT (Grünberg et al., 2020; Way and Lapalme, 2021). The tundra shrub vegetation in Adventdalen raises up to only a few cm over the ground (personal observations), limiting its effect on ALT. Additionally, the vascular plant vegetation cover was correlated with air temperatures (See appendix, Fig. 5.2), making the effect of plant cover on ALT difficult to distinguish from the effect of air temperatures. The inclusion of vascular plant cover as an explanatory variable in the models was therefore not implemented. If similar studies are to be done in ecosystems with taller vegetation, controlling for its potential impact on ALT could be relevant.

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Conclusion

Based on results from models on data from disturbed and control plots, simulated grubbing applied in early summer cannot be said to have any significant impact on soil temperature nor active layer thickness (ALT) over one growing season. Soil temperature and ALT do, as expected, depend on organic and bryophyte layer thickness (OLT), which insulates the ground from temperature changes and mitigates impacts on ALT. The bryophyte layer would most likely require more heavy disturbance over multiple years in order to be disrupted to a degree where it generates any significant impact on soil temperature and ALT. Future research would also benefit from implementing registrations of environmental factors over the whole year, as winter conditions are shown to influence ALT.

Natural grubbing in the vicinity of the field site shows that grubbing by geese has the potential to cause large-scale disturbance on vegetation. This will most likely require years to reestablish. Long-term effects of large-scale grubbing is a topic with little prior research (Van der Wal et al., 2020). Therefore, whether grubbing of higher intensities covering larger areas could affect ALT on larger time scales needs more research, as destabilization of permafrost could have critical effects, both on local ecosystems and larger global scales.

References

- Abolt, C.J., Young, M.H., Atchley, A.L., Harp, D.R., 2018. Microtopographic control on the ground thermal regime in ice wedge polygons. *The Cryosphere* 12, 1957–1968.
- Abraham, K.F., Jefferies, R.L., Rockwell, R.F., 2005. Goose-induced changes in vegetation and land cover between 1976 and 1997 in an Arctic coastal marsh. *Arctic, Antarctic, and Alpine Research* 37, 269–275.
- Anderson, H.B., Godfrey, T.G., Woodin, S.J., Van Der Wal, R., 2012. Finding food in a highly seasonal landscape: where and how pink footed geese *anser brachyrhynchus* forage during the arctic spring. *Journal of Avian Biology* 43, 415–422.
- Atchley, A.L., Coon, E.T., Painter, S.L., Harp, D.R., Wilson, C.J., 2016. Influences and interactions of inundation, peat, and snow on active layer thickness. *Geophysical Research Letters* 43, 5116–5123.
- Beaulieu, J., Gauthier, G., Rochefort, L., 1996. The growth response of graminoid plants to goose grazing in a High Arctic environment. *Journal of Ecology* , 905–914.
- Beer, C., Zimov, N., Olofsson, J., Porada, P., Zimov, S., 2020. Protection of permafrost soils from thawing by increasing herbivore density. *Scientific reports* 10, 1–10.
- Biskaborn, B.K., Smith, S.L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D.A., Schoeneich, P., Romanovsky, V.E., Lewkowicz, A.G., Abramov, A., et al., 2019. Permafrost is warming at a global scale. *Nature communications* 10, 1–11.
- Cable, S., Elberling, B., Kroon, A., 2018. Holocene permafrost history and cryostratigraphy in the High-Arctic Adventdalen valley, central Svalbard. *Boreas* 47, 423–442.
- Christiansen, H.H., 2005. Thermal regime of ice-wedge cracking in Adventdalen,

- Svalbard. Permafrost and Periglacial Processes 16, 87–98.
- Clayton, L.K., Schaefer, K., Battaglia, M.J., Bourgeau-Chavez, L., Chen, J., Chen, R.H., Chen, A., Bakian-Dogaheh, K., Grelik, S., Jafarov, E., et al., 2021. Active layer thickness as a function of soil water content. *Environmental Research Letters* 16, 055028.
- Constable, A.J., Harper, S., Dawson, J., Holsman, K., Mustonen, T., Piepenburg, D., Rost, B., 2022. Cross-Chapter Paper 6: Polar Regions. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. In Press.
- Descamps, S., Aars, J., Fuglei, E., Kovacs, K.M., Lydersen, C., Pavlova, O., Pedersen, Å.Ø., Ravolainen, V., Strøm, H., 2017. Climate change impacts on wildlife in a High Arctic archipelago, Svalbard, Norway. *Global Change Biology* 23, 490–502.
- Eischeid, I., Soininen, E.M., Assmann, J.J., Ims, R.A., Madsen, J., Pedersen, Å.Ø., Pirotti, F., Yoccoz, N.G., Ravolainen, V.T., 2021. Disturbance mapping in Arctic tundra improved by a planning workflow for drone studies: Advancing tools for future ecosystem monitoring. *Remote Sensing* 13, 4466.
- Elmendorf, S.C., Henry, G.H., Hollister, R.D., Björk, R.G., Bjorkman, A.D., Callaghan, T.V., Collier, L.S., Cooper, E.J., Cornelissen, J.H., Day, T.A., et al., 2012. Global assessment of experimental climate warming on tundra vegetation: heterogeneity over space and time. *Ecology letters* 15, 164–175.
- Fox, A., Francis, I.S., Bergersen, E., 2006. Diet and habitat use of Svalbard pink-footed geese *anser brachyrhynchus* during arrival and pre-breeding periods in adventdalen. *Ardea* 94, 691–699.
- Fox, A., Madsen, J., Boyd, H., Kuijken, E., Norriss, D., Tombre, I., Stroud, D., 2005. Effects of agricultural change on abundance, fitness components and distribution of two Arctic-nesting goose populations. *Global Change Biology* 11, 881–893.
- Godínez-Alvarez, H., Herrick, J., Mattocks, M., Toledo, D., Van Zee, J., 2009. Comparison of three vegetation monitoring methods: Their relative utility for ecological assessment and monitoring. *Ecological indicators* 9, 1001–1008.
- Gornall, J., Jónsdóttir, I., Woodin, S., Van der Wal, R., 2007. Arctic mosses

- govern below-ground environment and ecosystem processes. *Oecologia* 153, 931–941.
- Gornall, J.L., Woodin, S.J., Jónsdóttir, I.S., Van der Wal, R., 2009. Herbivore impacts to the moss layer determine tundra ecosystem response to grazing and warming. *Oecologia* 161, 747–758.
- Grünberg, I., Wilcox, E.J., Zwieback, S., Marsh, P., Boike, J., 2020. Linking tundra vegetation, snow, soil temperature, and permafrost. *Biogeosciences* 17, 4261–4279.
- Hanssen-Bauer, I., Førland, E., Hisdal, H., Mayer, S., Sandø, A., Sorteberg, A., 2019. Climate in Svalbard 2100 - A knowledge base for climate adaptation. Norwegian Environment Agency (Miljødirektoratet).
- Harry, D., Gozdzik, J., 1988. Ice wedges: growth, thaw transformation, and palaeoenvironmental significance. *Journal of Quaternary Science* 3, 39–55.
- Heldbjerg, H., Madsen, J., Amstrup, O., Bakken, J., Balsby, T.T., Christensen, T.K., Clausen, K.K., Cottaar, F., Frikke, J., Gundersen, O.M., et al., 2020. Pink-footed goose Svalbard population status report 2019-2020 .
- Jasmin, J.N., Rochefort, L., Gauthier, G., 2008. Goose grazing influences the fine-scale structure of a bryophyte community in Arctic wetlands. *Polar Biology* 31, 1043–1049.
- Jefferies, R.L., Rockwell, R.F., 2002. Foraging geese, vegetation loss and soil degradation in an Arctic salt marsh. *Applied vegetation science* 5, 7–16.
- Jorgenson, M.T., Kanevskiy, M., Shur, Y., Moskalenko, N., Brown, D., Wickland, K., Striegl, R., Koch, J., 2015. Role of ground ice dynamics and ecological feedbacks in recent ice wedge degradation and stabilization. *Journal of Geophysical Research: Earth Surface* 120, 2280–2297.
- Kenkel, N., 2006. On selecting an appropriate multivariate analysis. *Canadian Journal of Plant Science* 86, 663–676.
- Kotanen, P.M., Jefferies, R.L., 1997. Long-term destruction of Sub-Arctic wetland vegetation by lesser snow geese. *Ecoscience* 4, 179–182.
- Lachenbruch, A.H., Marshall, B.V., 1986. Changing climate: geothermal evidence from permafrost in the alaskan arctic. *Science* 234, 689–696.
- Lang, S.I., Cornelissen, J.H., Shaver, G.R., Ahrens, M., Callaghan, T.V., Molau, U.,

- Ter Braak, C.J., Hölzer, A., Aerts, R., 2012. Arctic warming on two continents has consistent negative effects on lichen diversity and mixed effects on bryophyte diversity. *Global Change Biology* 18, 1096–1107.
- Lett, S., Jónsdóttir, I.S., Becker-Scarpitta, A., Christiansen, C.T., During, H., Ekelund, F., Henry, G.H., Lang, S., Michelsen, A., Rousk, K., et al., 2021. Can bryophyte groups increase functional resolution in tundra ecosystems? *Arctic Science* .
- Mackay, J.R., MacKay, D., 1974. Snow cover and ground temperatures, Garry Island, NWT. *Arctic* , 287–296.
- Matsuoka, N., Christiansen, H.H., Watanabe, T., 2018. Ice-wedge polygon dynamics in Svalbard: Lessons from a decade of automated multi-sensor monitoring. *Permafrost and Periglacial Processes* 29, 210–227.
- MET Norway (The Norwegian Meteorological Institute), . Norwegian Centre for Climate Services. URL: <https://seklima.met.no/>. Accessed: 2022.02.09.
- Natali, S.M., Holdren, J.P., Rogers, B.M., Treharne, R., Duffy, P.B., Pomeroy, R., MacDonald, E., 2021. Permafrost carbon feedbacks threaten global climate goals. *Proceedings of the National Academy of Sciences* 118.
- Pedersen, Å.Ø., Paulsen, I.M., Albon, S., Arntsen, G.B., Hansen, B.B., Langvatn, R., Loe, L.E., Le Moullec, M., Overrein, Ø., Peeters, B., et al., 2019. Svalbard reindeer (*Rangifer tarandus platyrhynchus*): a status report. The Norwegian Polar Institute.
- Peeters, B., Pedersen, Å.Ø., Loe, L.E., Isaksen, K., Veiberg, V., Stien, A., Kohler, J., Gallet, J.C., Aanes, R., Hansen, B.B., 2019. Spatiotemporal patterns of rain-on-snow and basal ice in High Arctic Svalbard: detection of a climate-cryosphere regime shift. *Environmental Research Letters* 14, 015002.
- Petit Bon, M., Böhner, H., Bråthen, K.A., Ravolainen, V.T., Jónsdóttir, I.S., 2021. Variable responses of carbon and nitrogen contents in vegetation and soil to herbivory and warming in High-Arctic tundra. *Ecosphere* 12, e03746.
- Pointing, S.B., Büdel, B., Convey, P., Gillman, L., Koerner, C., Leuzinger, S., Vincent, W.F., 2015. Biogeography of photoautotrophs in the high polar biome. *Frontiers in plant science* 6, 692.
- Ravolainen, V., Soiminen, E.M., Jónsdóttir, I.S., Eischeid, I., Forchhammer, M., Van der Wal, R., Pedersen, Å.Ø., 2020. High Arctic ecosystem states: Conceptual models of vegetation change to guide long-term monitoring and

- research. *Ambio* 49, 666–677.
- Schuur, E.A., Bockheim, J., Canadell, J.G., Euskirchen, E., Field, C.B., Goryachkin, S.V., Hagemann, S., Kuhry, P., Lafleur, P.M., Lee, H., et al., 2008. Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. *BioScience* 58, 701–714.
- Schuur, E.A., McGuire, A.D., Schädel, C., Grosse, G., Harden, J.W., Hayes, D.J., Hugelius, G., Koven, C.D., Kuhry, P., Lawrence, D.M., et al., 2015. Climate change and the permafrost carbon feedback. *Nature* 520, 171–179.
- Shaver, G.R., Billings, W.D., Chapin, F.S., Giblin, A.E., Nadelhoffer, K.J., Oechel, W.C., Rastetter, E., 1992. Global change and the carbon balance of Arctic ecosystems. *BioScience* 42, 433–441.
- Soudzilovskaia, N.A., van Bodegom, P.M., Cornelissen, J.H., 2013. Dominant bryophyte control over high-latitude soil temperature fluctuations predicted by heat transfer traits, field moisture regime and laws of thermal insulation. *Functional Ecology* 27, 1442–1454.
- Speed, J.D., Cooper, E.J., Jónsdóttir, I.S., Van Der Wal, R., Woodin, S.J., 2010a. Plant community properties predict vegetation resilience to herbivore disturbance in the Arctic. *Journal of Ecology* 98, 1002–1013.
- Speed, J.D., Woodin, S., Tømmervik, H., Van der Wal, R., 2010b. Extrapolating herbivore-induced carbon loss across an Arctic landscape. *Polar biology* 33, 789–797.
- Speed, J.D., Woodin, S.J., Tømmervik, H., Tamstorf, M.P., Van Der Wal, R., 2009. Predicting habitat utilization and extent of ecosystem disturbance by an increasing herbivore population. *Ecosystems* 12, 349–359.
- Staaland, H., 1984. On the quality of Svalbard reindeer pasture in the summer and autumn. *Rangifer* 4, 16–23.
- Ståhl, G., Ekström, M., Dahlgren, J., Esseen, P.A., Grafström, A., Jonsson, B.G., 2020. Presence–absence sampling for estimating plant density using survey data with variable plot size. *Methods in Ecology and Evolution* 11, 580–590.
- Tyler, N.J., Forchhammer, M.C., Øritsland, N.A., 2008. Nonlinear effects of climate and density in the dynamics of a fluctuating population of reindeer. *Ecology* 89, 1675–1686.
- Van Der Wal, R., Sjögersten, S., Woodin, S.J., Cooper, E.J., Jónsdóttir, I.S., Kuijper,

- D., Fox, T.A., Huiskes, A., 2007. Spring feeding by pink-footed geese reduces carbon stocks and sink strength in tundra ecosystems. *Global Change Biology* 13, 539–545.
- Van der Wal, R., 2006. Do herbivores cause habitat degradation or vegetation state transition? Evidence from the tundra. *Oikos* 114, 177–186.
- Van der Wal, R., Anderson, H., Stien, A., Loe, L.E., Speed, J., 2020. Disturbance, recovery and tundra vegetation change: Final report project 17/92-to Svalbard Environmental Protection Fund.
- Van der Wal, R., Brooker, R., 2004. Mosses mediate grazer impacts on grass abundance in Arctic ecosystems. *Functional Ecology* 18, 77–86.
- Watanabe, T., Matsuoka, N., Christiansen, H.H., Cable, S., 2017. Soil physical and environmental conditions controlling patterned-ground variability at a continuous permafrost site, Svalbard. *Permafrost and Periglacial Processes* 28, 433–445.
- Way, R., Lapalme, C., 2021. Does tall vegetation warm or cool the ground surface? Constraining the ground thermal impacts of upright vegetation in northern environments. *Environmental Research Letters* 16, 054077.
- Wilcox, E.J., Keim, D., de Jong, T., Walker, B., Sonnentag, O., Sniderhan, A.E., Mann, P., Marsh, P., 2019. Tundra shrub expansion may amplify permafrost thaw by advancing snowmelt timing. *Arctic Science* 5, 202–217.
- Williams, L., Borchhardt, N., Colesie, C., Baum, C., Komsic-Buchmann, K., Rippin, M., Becker, B., Karsten, U., Büdel, B., 2017. Biological soil crusts of arctic svalbard and of livingston island, antarctica. *Polar Biology* 40, 399–411.
- Zibulski, R., Herzsuh, U., Pestryakova, L.A., 2016. Vegetation patterns along micro-relief and vegetation type transects in polygonal landscapes of the Siberian Arctic. *Journal of Vegetation Science* 27, 377–386.

Appendix

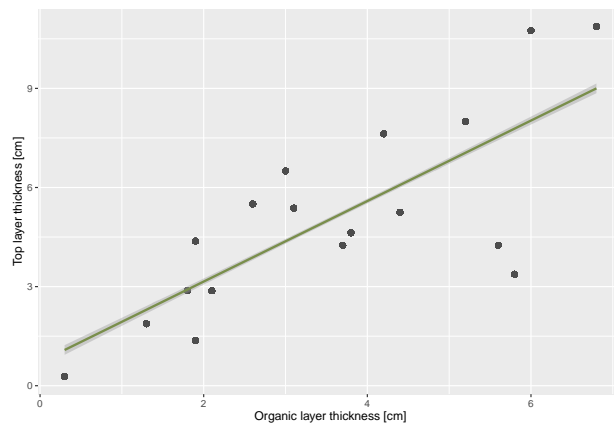


Figure 5.1: Correlation of the top (bryophyte) layer thickness and the organic layer thickness in all plots. A linear regression is presented as a green trend line, with 95% confidence intervals in grey.

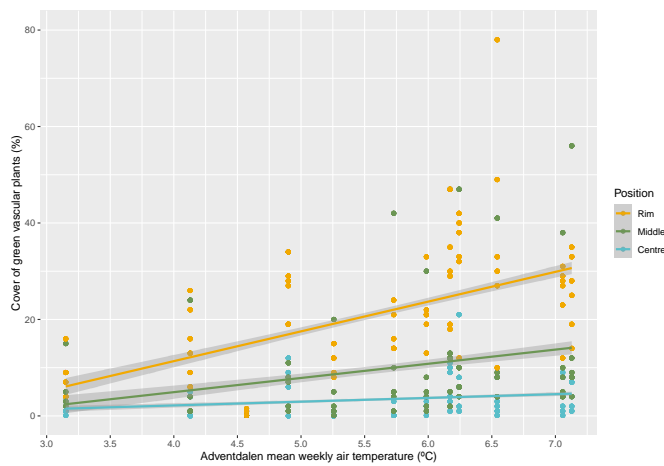


Figure 5.2: Weekly percentage cover of vascular plants plotted against Adventdalen weather station mean weekly air temperatures, in rim (yellow), middle (green) and centre (blue) positions. Linear regressions for each position are presented as trend lines, with 95% confidence intervals in grey.

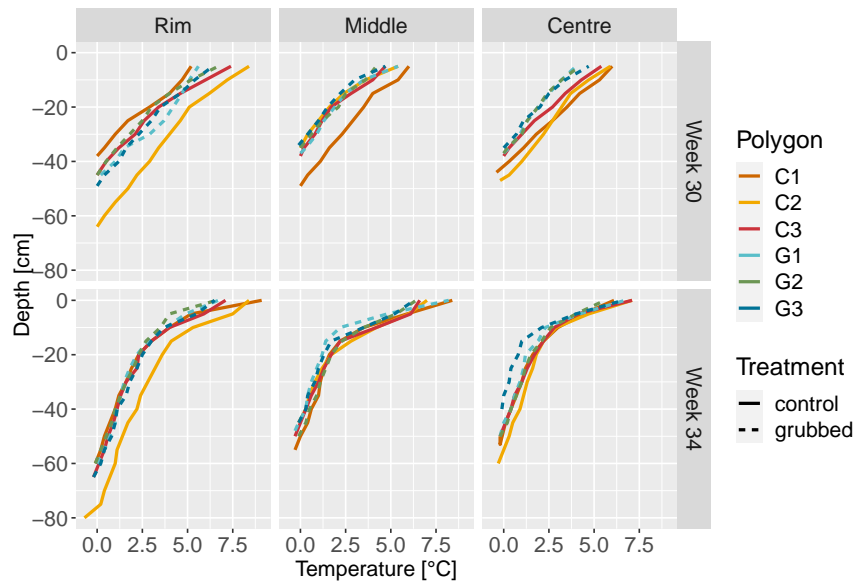


Figure 5.3: Temperatures at depth intervals from ground surface until reaching the ice layer, measured in each plot in week 30 (27th July) and 34 (24th August). Data from grubbed plots are presented as dashed lines.

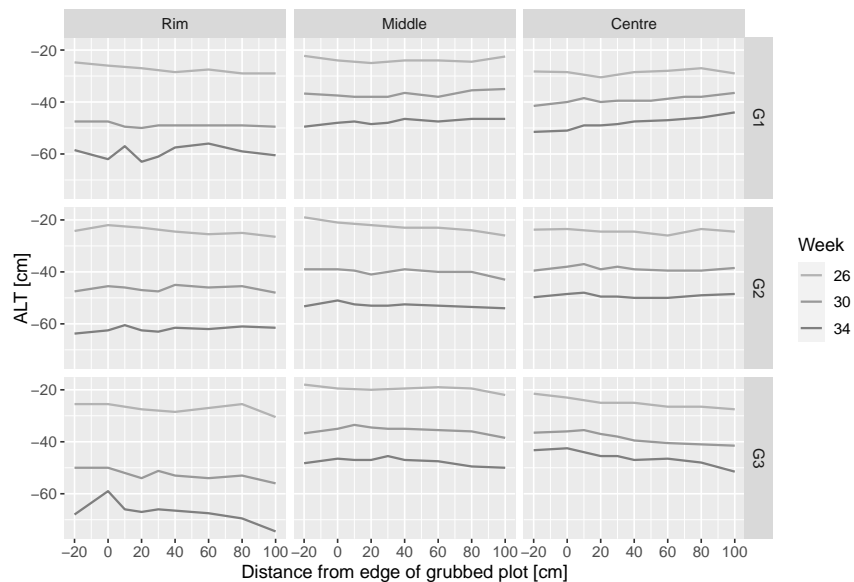


Figure 5.4: Transect of active layer thickness (ALT) conducted at monthly intervals (29th June, 27th July and 24th August) in grubbed plots. ALT was recorded within the plot (-20cm from edge), then at the edge of the plot towards north-east and extending 10cm, 20cm, 30cm, 40cm, 60cm, 80cm and 100cm beyond the plot.

Table 5.1: Counts of presence and absence of functional groups within each quadrat square of each plot. Bryophyte functional groups are shortened to BT (Branched turf), LL (Leafy liverworts), Po (Polytrichales), Sp (Sphagnum) and SU (Short unbranched turf).

plot_id	polygon_id	treatment	position	date	Forbs	Deciduous shrubs	Grasses	Sedges	Rushes	Horsetails	BT	SU	Po	Sp	LL	Foliose lichen	Crust
C1rim	C1	control	rim	19.07.2021	25	25	25	0	1	0	8	18	16	0	0	8	0
C1mid	C1	control	middle	19.07.2021	20	24	25	0	0	16	9	25	25	6	0	3	0
C1cen	C1	control	centre	23.07.2021	0	0	0	25	0	0	25	0	0	0	0	0	0
G1rim	G1	grubbed	rim	19.07.2021	24	25	25	0	0	25	17	15	15	0	4	18	0
G1mid	G1	grubbed	middle	19.07.2021	0	7	25	0	0	0	7	24	25	0	0	0	0
G1cen	G1	grubbed	centre	23.07.2021	0	0	7	4	0	9	25	0	0	0	0	0	0
C2rim	C2	control	rim	21.07.2021	5	25	24	0	0	25	0	2	6	0	0	0	25
C2mid	C2	control	middle	21.07.2021	14	25	25	0	0	25	0	25	4	0	1	3	0
C2cen	C2	control	centre	23.07.2021	0	0	15	0	0	0	25	0	0	0	0	0	0
G2rim	G2	grubbed	rim	19.07.2021	21	25	25	4	0	25	0	11	23	0	0	0	0
G2mid	G2	grubbed	middle	19.07.2021	0	7	25	0	0	0	0	1	25	0	0	0	0
G2cen	G2	grubbed	centre	23.07.2021	0	0	0	23	0	0	25	0	0	0	0	0	0
C3rim	C3	control	rim	21.07.2021	25	25	25	8	0	0	21	8	22	0	2	16	0
C3mid	C3	control	middle	21.07.2021	0	21	25	0	0	0	4	25	10	0	0	3	0
C3cen	C3	control	centre	23.07.2021	0	0	0	25	0	0	25	0	0	0	0	0	0
G3rim	G3	grubbed	rim	21.07.2021	25	15	25	0	2	0	0	8	25	0	0	1	0
G3mid	G3	grubbed	middle	21.07.2021	24	25	25	0	0	0	0	25	25	0	0	1	0
G3cen	G3	grubbed	centre	23.07.2021	0	0	7	3	0	0	25	0	0	0	0	0	0

