Faculty of Biosciences, Fisheries and Economics

Department of Arctic and Marine Biology

Recovery potential of Arctic wetland tundra on Svalbard

Long-term impacts of grazing by barnacle geese (Branta leucopsis) within the context of climate change

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Karolina Paquin

Master's thesis in Biology BIO-3950 - May 2014

Supervisor: Professor Elisabeth Cooper, UIT The Arctic University of Norway
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Cover Photo: Block WB and WA of field site in Adventdalen, Svalbard.

Photo taken by Karolina Paquin

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1 Abstract

The substantial increase of the migratory Svalbard population of Barnacle geese *Branta leucopsis* during the past 50 years has been attributed to a warming climate, changes in agricultural land use, and conservation measures. The geese are likely to continue to forage and reproduce in Arctic wetlands in increasing numbers. This project revisited the experimental plots from an earlier experiment (FRAGILE) on goose grazing and climate warming to assess the long-term recovery potential of wet tundra plant communities from the grazing disturbance applied 8 years prior. Recovery was defined as comparable above ground biomass and community composition of control and grazed treatments, and it was expected to detect the influence of high grazing pressure, and for this response to differ under warmed conditions. Grazing and OTCs were combined in a fully factorial design, with 3 summers of grazing pressure applied using captured barnacle geese to simulate natural and high applied, and 10 years of simulated conditions of climate warming using OTCs. OTCs increased the air temperature, but decreased the soil temperature. In ambient treatment, no effect of grazing was detected for the functional groups but biomass responded positively to 5 hour grazing treatment. In OTCs, the biomass responded positively in 1 hour treatment, functional groups pteridophytes and graminoids responded positively in all grazing levels, and bryophytes only in ungrazed. Presence of rarer species fluctuated over the years, while the dominant forage species *Dupontia* sp, *Eriophorum scheuchzeri, Cardamine nymanii, Equisetum arvense* and *Calliergon richardsonii* have remained ubiquitous in all years. Thus, the positive impact of grazing on biomass and response of certain functional groups was still detectable eight years after intense goose grazing and ten years of continuous warming, suggesting that Arctic tundra wetlands are slow to recover from intensified grazing disturbance.

Keywords: Arctic, tundra, plant communities, barnacle geese, goose grazing, OTC

2 Introduction

Substantial increases in populations of migratory geese in the circumpolar arctic in the past 50 years have been attributed to a warming climate, changes in agricultural land use, and conservation measures in North America and Europe (Fox et al. 2005; Gauthier et al. 2005; Van Eerden et al. 2005). Since the 1950s, geese have responded to increased habitat fragmentation, loss of traditional wetland feeding grounds and better foraging opportunities by transitioning to intensively farmed land in their over-wintering stages (Fox et al. 2005). As a result of decades of nitrogen fertilization, farmed land served as an agricultural subsidy that provided far superior foraging opportunities. With better nutrient and energy intake over winter and spring staging phases, reproductive success increased in transitioned populations (Fox et al. 2005; Van Eerden 2005 and Abraham et al. 2005). Methods to manage these increases are being negotiated (Madsen and Williams 2011), but the geese are likely to continue exploiting the available crops and continue to forage and reproduce in the Arctic in increasing numbers (Van Eerden et al. 2005).

The effects of population increase is seen in the staging and breeding grounds of the geese on the Arctic tundra, where the destructive repercussions of intense grazing pressure can result in the complete change of vegetative state to an alternative stable state of exposed sediments, as in the case of lesser snow geese *Chen caerulescens caerulescens L.* around Hudson Bay, Canada (Abraham et al. 2005; Jefferies et al. 2006). The recovery time of such plant communities is unknown, and estimated to take multiple decades to re-establish again. For this reason, agreements such as the African-Eurasian Water Bird Agreement have management programs (Madsen and Williams 2012) in development for goose populations in conflict with human economic interests. For example, the Svalbard population of Pink-footed geese has been a test case since 2009 to manage a stable population limit and prevent damage to Svalbard tundra by regulating the developing agricultural practices and hunting practices in mainland Europe.

This study is based on the EU funded FRAGILE experiment (Fragility of Arctic goose habitat: Impacts of land use, conservation and elevated temperature; contract no. EVK2-2001-00235) initiated in 2003 in Adventdalen on Svalbard (Cooper et al. 2004), with the aim to study the impact of goose grazing on High Arctic tundra, but within the context of rapidly warming conditions in Arctic (Houghton et al. 2001; Maxwell 1992; McBean et al. 2005; Mitchell et al. 1995). The impact of goose grazing was experimentally manipulated by applying three levels of grazing by barnacle geese to mesic and wet tundra sites: no grazing, 1 hour and 5 hours of grazing, which corresponded to control, ambient levels of grazing, and 2.2 to 3.7 times the pressure of ambient grazing (Kjuiper et al. 2006; Sjögersten et al. 2008). The short-term effects of goose grazing and warming on plant recovery (Cooper et al. 2004; Cooper et al. 2006), soil carbon cycles (Strebel et al. 2010; Van der Wal et al. 2007), seed banks (Kuijper et al. 2006), nitrogen fertilization (Sjögersten et al. 2011), and resilience of tundra ecosystems to increased disturbance have been described (Sjögersten et al. 2012) from the FRAGILE site. However, there remains the question of long-term recovery of wet tundra habitats from intense goose grazing pressure that would result from unregulated increases in goose populations of the barnacle goose *Branta leucopsis*. This has been analyzed recently by researchers with access to reliable long term data on pink footed and barnacle geese in Greenland (Madsen et al. 2011), and found very strong positive responses to warming by above ground biomass, no change in plant composition in response to grazing. Essentially, we assess the recovery of plant communities by asking how persistent the effects of goose grazing are in ambient conditions, and if this is different under simulated conditions of future climate conditions.

2.1 SVALBARD GEESE –LIFE STAGES AND FEEDING HABITS

The Svalbard population of barnacle geese overwinter in the UK (See Figure 1 in Appendix) and migrate to summer breeding grounds on the Arctic tundra. The population has increased from 300 in 1940 (Owen and Norderhaug 1977) to 23 000 in 1996 (Pettifor et al. 1998), for the same reasons enumerated earlier. The foraging performance of geese between migratory stages is critical for reproductive success on Svalbard (Black et al. 1991; Prop et al. 2003; Prop and Black 1998), where feeding on the tundra to a variable degree replaces fat and protein lost during migration in preparation for egg laying (Hahn et al. 2011). Not only are the costs of migration high, geese having poor digestion efficiency (Mattocks 1971; Owen 1980; Prop and Vulink 1992; Van der Wal and Loonen 1998) necessitates preferential foraging for high quality plants (Prop et al. 1980; Prop and Deerenberg 1991) in wet moss tundra (Alsos et al. 1998).

Barnacle geese graze above ground biomass by pecking, and prefer to forage in wet moss dominated tundra (Cooper et al. 2004). Graminoids swards are consumed as multiple tillers of variable length with highest intake rates in swards of 85mm in winter pasture lands (Lang and Black 2001; Van der Graaf et al. 2006). Alsos et al. (1998) analysed the dietary component of grazed vegetation by incubating females, and found 41% ford flowers, 19% grasses, 6% leaves and buds of forbs and 34% mosses, with a switch to less nutritious moss (Prins 1981; Speed et al 2009) when energy rich plants were less available. Moss intake tended to decrease with increased availability of graminoids (Alsos 1998; Soininen et al 2010). Species favoured by geese in FRAGILE plots were *Equisetum arvense, Dupontia* sp and least favoured were moss (Cooper et al. 2004).

2.2 EFFECTS OF GRAZING ON BIOMASS AND COMMUNITY COMPOSITION

As herbivores, barnacle geese inflict disturbance on wet tundra plant communities through selective grazing, trampling and nutrient input (Bruun et al. 2008; Van der Wal 2001). Tundra recovery to disturbance is expected to be slow due to the short growing season, net primary productivity, and nitrogen limitation (Bliss et al. 1986**;** Chapin and Shaver 1985). On the other hand, according to the grazing optimization hypothesis, grazing intensity increases aboveground primary production (ANPP) to an optimal level, above which ANPP decreases to below ungrazed communities (McNaughton 1979). The short term overcompensation occurs when plants respond to grazing pressure by allocating more resources to above ground growth to the detriment of below ground development (Beaulieu et al. 1996), potentially facilitated by the nutrient supplement from the feces of the herbivore (Ruess and MacNaughton 1984; Coughenour and Singer 1990; Coughenour 1991). The short-term effects on tundra vegetation by Arctic herbivores have been extensively reviewed (Mulder et al. 1999), with generally positive or no change in above ground biomass production and change in community composition as an interaction between herbivores and abiotic conditions. Few studies are available for wet tundra and barnacle geese (Cooper et al. 2004; Cooper et al. 2006; Gauthier et al. 2006; Van der Wal 2001; Wegener and Odasz 1997), but there are similar studies on grazing lesser snow geese in Canada (Gauthier et al. 1998; Beaulieu et al. 1996). In the short-term, moderate levels of grazing increase biomass a small amount or not at all, likely due to the absorption of nutrients from feces by the thick layer of moss typically found in wet tundra habitats (Gauthier et al. 2006; Gornall et al. 2009; Pineau 1999) instead of vascular species. The roots of vascular plants are buried deep in the moss, and are unable to absorb the majority of nutrient input (Gauthier et al. 2006). Also, grazing by barnacle geese is much less destructive than grubbing by greater and lesser snow geese in Canada and pink-footed geese on Svalbard, where underground parts of plants are removed (Zacheis et al. 2001).

Response to grazing is species and habitat dependant; a weak and no over compensatory response was found for *Dupontia fisherii* (Cooper et al. 2006; Gauthier 2006). In an exclosure experiment, 5 years of recovery from moderate to higher goose grazing resulted in a fivefold increase in biomass of the preferred foraged species *Eriophorum scheuchzeri*, no response by *Dupontia fisheri*, and overall increase in biomass of graminoids from 52g/m^2 after two years to 87 g/m^2 (Gauthier et al. 2006). Long term response was also minor or non-existent (Bakker and Loonen 1998; Jefferies 1994; Van der Graaf 2006), and the most recent study found no change in species composition, decrease in abundance of graminoids and appearance of bare ground (Madsen et al. 2011) due to 26 years of intensified goose grazing.

2.3 EFFECTS OF CLIMATE CHANGE ON BIOMASS AND COMMUNITY COMPOSITION

General trends in the response to growing season warming include increase in vegetation cover, canopy height, above ground biomass, abundance of shrubs, and stable or increasing graminoids and forbs and decrease in bryophytes and lichens (Elmendorf et al. 2012b; Hollister 2003; Hudson and Henry 2010; Hudson et al. 2011; Walker et al. 2006). Strong responses to warming have been detected in terms of plant biomass, for example above ground graminoids increased as much as 84% on Bylot Island Canada from 1990 and 2007 (Cadieux et al. 2008) and the doubling of moss fen aboveground biomass from 1982 to 2008 in Eastern Greenland (Madsen et al. 2011). These trends are oversimplifications, as experiments showing contrasting changes and even resilience to change in biomass (Hollister et al. 2005b) and community composition (Hudson and Henry 2010). Strong site specific differences imply regionally specific responses, where responses are due more to the interaction with local temperature, moisture and duration of warming (Elmendorf et al. 2012a). The meta-analysis by Elmendorf et al. (2012a) found greater abundance responses in wet sites, with sedges exhibiting the most positive and amongst graminoids and decrease of bryophytes and lichens. The site is dominated by few species, notably the one species of pteridophyte *Equisetum arvense*, whose close relative *Equisetum fluvialis* has been shown to respond positively in terms of biomass and size to warming treatment in Southern Finland (Ojala et al. 2001).

Climate warming effects have been addressed as manipulated experiments in the tundra of circumpolar Arctic in numerous studies as part of ITEX, the international tundra experiment (Henry and Molau 1997; Molau and Møgaard 1996). A common technique to manipulate temperature within the context of climate change projection of 1-2°C is the use of Open Top Chambers (OTCs)(Marion et al. 1997), which have been used in sites across the Arctic and Antarctic to warm plots by about 1.2-1.8°C, but are known to decrease soil temperature in wetter habitats in the FRAGILE wet plots (Cooper et al. 2006) and other parts of the Arctic (Dabros et al. 2010; Sjögersten et al. 2012), potentially negating the positive influence of a warmer climate (Van der Wal et al. 2001).

2.4 GRAZING AND CLIMATE CHANGE –INTERACTION WITHIN TUNDRA PLANT COMMUNITIES

Previous studies by Post and Pedersen (2008) and Klein (2007) on the interaction of grazing and climate warming suggest a synergistic interaction, where grazing by large herbivores such as muskoxen and caribou in Greenland, and other grazing species on the Tibetan Plateau mediated the effects of warming. They found contrasting trends due to warming in aboveground biomass production, shifts in communities from graminoid to shrub dominated, and both effects were reduced or reversed by grazing. Furthermore, when grazers are removed, plant community diversity was found to be reduced under warming conditions (Post 2014), suggesting that herbivore play a key role in maintaining the species diversity in a warmer climate. Gornall et al. (2009) also found that moss layer, which is especially thick in the wet tundra habitat of this studies' field site, further complicates responses due to its role as an insulator and absorption of nutrient subsidies in goose faeces. Responses were enhanced by simulating removal of moss by grazers, and resulted in increases of graminoids and enhanced soil warming by warming treatment. When moss remained intact, no response was found for vascular plants, suggesting the importance of accelerated soil processes due to warming of soil.

In the specific case of wet Arctic tundra, a recent study of goose grazing and warming (Madsen et al. 2011) show increases in above ground biomass, no change in species composition and a decrease in frequency of graminoids, although these results are based on goose grubbing by pink-footed geese and grazing by barnacle geese.

Neither study addressed the long term impact of above ambient levels of grazing, thus this study aims to describe the recovery of wet tundra from ambient and high goose grazing pressure in the context of climate change predictions, defining recovery as comparable biomass and community composition between treatment and ungrazed sites in 2013. The field site has certain characteristics likely to influence the findings. First, it is composed of a thick layer of moss, which had been trampled by geese in the application of grazing in 2003, 2004 and 2005, especially in the 5 hour treatment (Cooper at al. 2004). This can be expected to influence long-term responses in terms of its influence on soil temperatures (Van der Wal 2001) and nutrient uptake (Pouliot 2009) critical for the positive response of above ground growth to warming and recovery from grazing. Biomass is estimated using total plant hits obtained by the point intercept method (Jonasson 1988; Redjadj et al. 2012), and community data derived from species composing the total hits (Godìnex-Alvarez et al. 2009). We expect to detect the effect of intense grazing on biomass and community composition 8 years after the grazing disturbance was applied; it is also expected that 10 years of continuous warming interact with the lingering effects of grazing by dampening responses.

3 Materials and Methods

3.1 SITE DESCRIPTION

The experiment was conducted in Adventdalen, 15 kilometers east of Longyearbyen (78°N, 16°E) on the west coast of Spitsbergen, Svalbard (Fig 2). This project was conducted in the experimental blocks of wet tundra meadow habitat at the outer edge of an alluvial fan on the south side of the valley (Figure 3). Melt water from Foxfønna glacier flowed through the site, forming a hydrological gradient between blocks. The project used the FRAGILE experiment set up, an international collaborative experiment that began in 2003 to investigate the impact of significant increases in goose populations that reproduce and feed on tundra ecosystems within the context of global warming (fragility of arctic goose habitat: impact of land use, conservation, and elevated temperature, EU project No. EVK2-2002-00235; Cooper et al. 2004; Cooper et al. 2006). Open top chambers (OTCs) were placed in wet tundra areas typical of preferred summer goose grazing sites. During the period 2003-2005, selected plots were grazed upon by barnacle geese for 1 hour or 5 hour periods to simulate average and the high grazing pressure that would be expected of substantial increases in population of geese (Kjuiper 2006; Loonen et al. 2000).

The growing season lasts June-August, when melt out of snow cover and 24 hours of daylight thaw an active layer about 70cm deep (Sjögersten et al. 2012). The bedrock is covered with fluvial silt and a shallow soil organic layer in drier places. In the wettest areas, the soil consists of thick poorly decomposed moss and silts up to 50cm and remains saturated for the growing season. The vegetation is dominated by thick moss (*Calliergon richardsonii, Sanionia uncinata, Drepnaclados revolvens, Aulocomnium palustre, Meesia triquestris*) interspersed with grasses (*Dupontia sp., Calamagrostis stricta, Poa sp.*), sedge (*Eriophorum scheuchzeri, Carez subspathacea, Carex glareosa*), pteridophytes (*Equisetum arvense*) and other herbs, forbs and dwarf shrubs (*Bistorta vivipara, Cardamine nymanii, Koenigia islandica, Salix polaris*) (Cooper et al. 2006; Strebel et al. 2010; Sjögersten et al. 2012).

Adventdalen is a valley with oceanic climate, and most annual precipitation falls in winter as snow. The area does not typically receive much precipitation in the summer, with the exception in the month of August 2013.The highest amount of precipitation that year fell that month with a diurnal maximum of 9 mm and total of 59 mm. Compared to an average monthly total value of 20 mm during the period 1983 to 2012, this was almost a threefold increase in summer precipitation. The average daily temperature in the summer 2013 was 7.2°C. See Table 1 in Appendix for average monthly temperature and precipitation in the summer months of 2003, 2005 and 2013 from the nearest Meteorological station. (Climate data available online at www.eklima.no)

3.2 FIELDWORK

Field work was conducted during the summer of 2013; using the same methods used by previous members of the group in 2003 and 2004.The site was set up from June 7-12, when the panels of the OTCs were cleaned to ensure maximum light penetration. The eighteen loggers available at the time were installed in plots, and the fourteen remaining loggers were installed July 4-6. The point frame data was collected from August 6-30, and pictures were taken of each plot using a camera and an aluminum stand (Fig 4 in Appendix) from July 7-9. Refer to Kuijper 2009 for full details of previous methods and design.

3.3 EXPERIMENTAL DESIGN

The experiment was set up as a randomized fully factorial block design with two factors: three levels of grazing (Ungrazed, 1 hour, 5 hour) and two levels of temperature manipulation (ambient, OTC). There are five replicate blocks, each containing six treatment combinations giving a total of thirty 2 x 2m plots. The blocks are separated by at least 10m, and all plots are accessed via boardwalks to minimize the damage caused by trampling. Grazing treatments were applied using adult captured barnacle geese (*Branta leucopsis*) from Ny-Ålesund in the years 2003, 2004 and 2005. They were placed in the plots for 1 or 5 hours, to simulate natural and intense grazing pressure respectively (Kjuiper et al. 2006). During the period 2003 to 2005, all blocks were fenced to prevent natural grazing by reindeer and other geese. Since its end in 2005, the plots have not been controlled for grazing pressure and OTCs on the wet site have not been removed. As for evidence of current ambient grazing, reindeer were seen in the 2013 field season once in the ambient plots, and visible footprints in the plots were noted.

Temperature was manipulated using OTCs, which have been in place since 2003. OTCs function as small greenhouses to simulate climate projections in the arctic, and are standard for use in tundra experiments. This project used OTCs based on ITEX design (International Tundra Experiment; Marion et al. 1997), hexagonal shape with panels of polycarbonate and dimension 0.5m x 1.5m (Sjögersten et al. 2012). They have been shown to warm the air temperature by about 1.5°C (Sjögersten et al. 2008), but decrease soil temperature in the FRAGILE wet site (Cooper et al. 2006; Sjögersten et al. 2012) and northwestern Quebec (Dabros et al. 2010). The soil was completely saturated by water in most plots, making it difficult to differentiate between soil and water temperature.

3.4 POINT INTERCEPT MEASUREMENTS

The point intercept method (Levy and Madden 1933; Stanton 1960) was used to collect data for total hits in each plot. The plot frame dimensions were 75 x 75 cm and contained 100 evenly distributed points. A probe was used at each point for hit data. At each point, the first species hit by the probe was recorded (named ‘first hit’). All subsequent hits in the canopy were also recorded. The total hits (sum of first and other hits) give a proxy for biomass (see discussion section) and community composition for each plot.

3.5 COMMUNITY DATA

Hits were identified down to species, and sorted according to functional grouping typically used when studying Arctic vegetation (Chapin et al. 1996). See Tables 6 to 8 in the Appendix for the 2013, 2005 and 2003 species lists of presence and absence in each treatment combination.

3.6 TEMPERATURE

Temperature data was collected using thirty-two Gemini Tiny Tag Loggers (TGP-4020 Tinytag Plus 2, TG12-0020 TinytagPlus, TG12-0017 [internal probe] TinytagPlus). Multiple models of probes were used (PB-5006 Flexible thermistor probe, PB-5001 Standard thermistor probe). Placement of loggers and probes was designed to maximise the use of equipment available and take in to account the geographical gradient (see Table 2 in Appendix).

Two loggers were used per plot to record soil and air temperature. Eight air loggers were shielded from sunlight using ACS-5050 Stevenson Type Screen (http://www.geminidataloggers.com/accessories/accessories/acs-5050), and eight using white recycled plastic containers cut in the sides to allow air flow. Models with internal probes were used in the shields, while the probe from probe models were attached within the recycled containers and anchored to the soil using recycled metal supports. Probe models were used for soil temperature. The loggers were tied to the boardwalks using string to keep them out of the water, and a channel was cut through the soil using a knife to thread the cable into the plot at an average depth of 7.4cm and height above the moss 9.4cm. The soil probe was placed adjacent to the air probes on the northern side of the plot. Eighteen loggers were installed on June 11th, and the other fourteen on July 4-6. The fourteen were placed later because they were not available for the June period of fieldwork. All were set to record intervals of half an hour on the hour for the field season and were removed on August 28.

All loggers were synchronised because they were started using the same laptop. Loggers were calibrated at the end of field season using buckets of ice water for probe models, which were then used to calibrate the internal probe loggers in fridges set to approximately two degrees celcius. It was important to calibrate to approximately zero, as summer temperatures on Svalbard remain low for most of the season.

3.7 SINKING OF THE OTCS

The OTCs have not been removed from the site since 2005, and have sunk into the soft, wet moss layer in the plots. The distance sunk was measured from the top of the moss layer to the bottom of the OTC at each or the six corners. Block WD was not measured due to investigator error. Table 3 in the appendix displays the average depth sunk in each block.

3.8 MOSS DEPTH

The depth of moss and soil was measured in each plot along two perpendicular transects, for a total of nine points per plot. They consisted of the centre point, four points 40cm from center, and four points 80 cm from centre. The center of the 2 x 2m plot was approximated using the meter sticks, allowing for some error due to significant movement of plot markers since the experiments initiation in 2003.

Two measurements were taken: sediment to base of live green moss and length of green moss. For most of the plots, the soil consisted of a heavily saturated layer of silt, dead brown moss and other poorly decayed plant matter. It was not possible to separate the dead moss and silt layer, as cutting into the plots to measure them would have caused considerable damage. Instead, the bedrock was reached by gently inserting the probe into the moss layer and feeling for a 'gravel' bottom. The live layer was measured as visibly growing moss, for example green *Calliergon richardsonii* or red-brown *Drepnaclados revolvens*. See Table 4 in appendix for average moss depths. Due to the uncertainty of the field measurements, data was not included in statistical analysis. It is addressed empirically, with the potential for future examination.

3.9 HYDROLOGY OF BLOCKS

Estimates of the hydrological gradient were measured in each plot using the aluminum probe in the SW corner of each plot, approximately 30 cm away from the plot marker. The locations were marked using a small wooden skewer to minimize the disturbance, and were revisited five times in August 2013. The OTC plots, measurements were taken outside and within the structure. The same technique mentioned in moss depth was used to locate the gravel bottom, where measurements were taken from and to the water surface. See Table 5 in appendix for average water depths. This data was not used in statistical analysis for the same reason as moss depths.

3.10 STATISTICAL ANALYSIS

Data analyses were conducted using the statistical program R 3.0.3 (R Core Team, 2013). Climatic data (Table 1 in Appendix) for the region was obtained from the weather station at

Svalbard Airport (78°N, 15°E; altitude 28m; from www.Eklima.no). Average monthly temperature was calculated from daily averages, and average monthly precipitation from total daily precipitation.

For all temperature logger data at the field site, half hour raw data was used for 2013 and hourly data for 2003. See Table 2 in Appendix for summary of logger placements. Two loggers were placed in every treatment; one for reading soil temperatures and one for reading air temperatures. There were 5 replicates in ungrazed plots of both OTC and ambient and 3 replicates in in 5 hour grazed treatments of both OTC and ambient. Using data recorded from site loggers, temperature sums were calculated as the sum of positive daily average temperatures over 0°C in 2013 when all 32 loggers were measuring temperature concurrently. This was to account for the different date and times the loggers were installed and removed from the field site. Logger temperature data was combined according to warming treatment and location in soil or air (Table 1 and Table 2), and further separated by grazing treatment (Table 2). Different numbers of days were sampled between years, because loggers were placed for a longer period than in 2003, therefore were not comparable statistically. Data from 2003 was reproduced from Cooper et al. (2006), but raw data was not available at the time to analyse in the same way as 2013 data.

Temperature logger data (Figure 6, Figure 7) was plotted using xyplot in package latticeExtra (Sarkar and Andrews 2013). All logger data was sorted as air ambient, air OTC, soil ambient and soil OTC to analyse the effect of OTCs on the air and soil temperature of plots. Differences in air between OTCs and control plots were analysed using t-test, after the data had been tested for normality using Shapiro Wilk. Differences in soil between OTCs and control were analysed using a non-parametric Kruskal Wallis test, as the data was not normal according to Shapiro Wilk. Differences between air and soil were analysed using non-parametric Wilcoxon signed rank test, as the data were not independent and soil temperatures not normally distributed.

Mean daily temperatures (Figure 6) were obtained by calculating the mean temperature for every day the loggers were installed at the field site (June 11th – August 28th), and averaged across all replicated loggers within each treatment (n=5 in ungrazed treatment, n=3 in 5 hour grazed treatment). It is important to note all available temperature data for 2013 was used in Figure 6, so not all replicates were running at the same time. Mean diurnal temperature (Figure 7) was calculated by taking the mean temperature of every hour and half hour raw data across the middle two weeks of June, July and August (11th-24th, 9th-22nd and 8th-21st respectively), and averaged across replicated loggers in each treatment. The data is presented as hourly over a period of 24 hours.

Dead plant hits were excluded from the analysis in 2013 to conform with previous years' methods, although it's been shown they respond positively to warming treatments (Wiedermann et al. 2007). Figures for total hits, community composition and logger time series were produced in the package sciplot (Morales 2012). Data was tested to respect normality and homogeneity of variance using Shapiro-Wilks test and Levene's test. Total Hit data required log transformation. Total Hit data was analysed as a proxy for biomass (see Discussion) using a two way analysis of variance fit to linear mixed models (Zuur et al. 2007) in the lme4 package (Bates et al. 2014) with block as a random factor. This was necessary to account for the hydrological gradient between blocks, which explained a significant amount of variance. Differences between means were further analysed using lsmeans in the package phia (Martìnez 2013a) when significant interactions between warming and grazing were found by the ANOVA (Martìnez 2013b), or Tukey's post hoc test when there was no significant interaction was found. Years were analyzed separately as they are repeated measures, and the focus of the experiment was to remain on 2013 data. Community data was analyzed using total hit data with the same method, separated into the functional groups graminoids, pteridophytes, forbs and bryophytes. Only one species of Pteridophyte was found in all plots, *Equisetum arvense*.

4 Results

4.1 TOTAL HITS

Figure 1 displays the log transformed total hits with standard error bars for all treatments in 2003, 2005 and 2013. Block was estimated as a random factor and data fitted to a linear mixed model with ungrazed ambient plots as the intercept (Effect sizes and output from fit displayed in Table 10 in Appendix).

In 2003, analysis of variance showed no effect of grazing or warming on total hits, but a significant interaction was found (F-value=9.646, *p*-value=0.001). At 5 hr grazing, total hits were reduced in OTCs (t-value= -2.544, *p*=0.019) and increased in ambient compared to ungrazed ambient, although it did not reach statistical difference according to the linear mixed model. Post hoc analysis of the interaction found total hits in 1 hr treatment of the OTCs to be higher than ambient (*p*<0.001).

In 2005, analysis of variance showed total hits varied with grazing treatment (F-value=5.401, *p*-value=0.013) and a significant interaction was found between warming and grazing (F-value=20.989, p-value<0.001). Compared to ungrazed ambient, the total hits were lower in 1 hr ambient plots (t-value=-2.101, *p*=0.048), increased in warmed 1 hr plots (t-value=2.254, *p*=0.036) and decreased in warmed 5 hr plots (t-value=-4.133, *p*<0.001). Post hoc analysis of the interaction found significant difference between OTC and ambient plots across all grazing levels, although according to ANOVA the effect of OTC was rejected marginally (F-value=3.951, *p*= 0.061)

In 2013, analysis of variance showed total hits varied with grazing treatment (F-value=6.308, *p*-value=0.007) and a significant interaction was found between warming and grazing (F-value=4.402, p-value=0.026). At 5 hr grazing, total hits were increased in ambient (t-value=3.559, *p*-value=0.002) and decreased in OTC, although it did not reach statistical difference according to the linear mixed model. Post hoc analysis of the interaction found that 1 hr warmed treatments contained higher total hits than ambient (*p*=0.020).

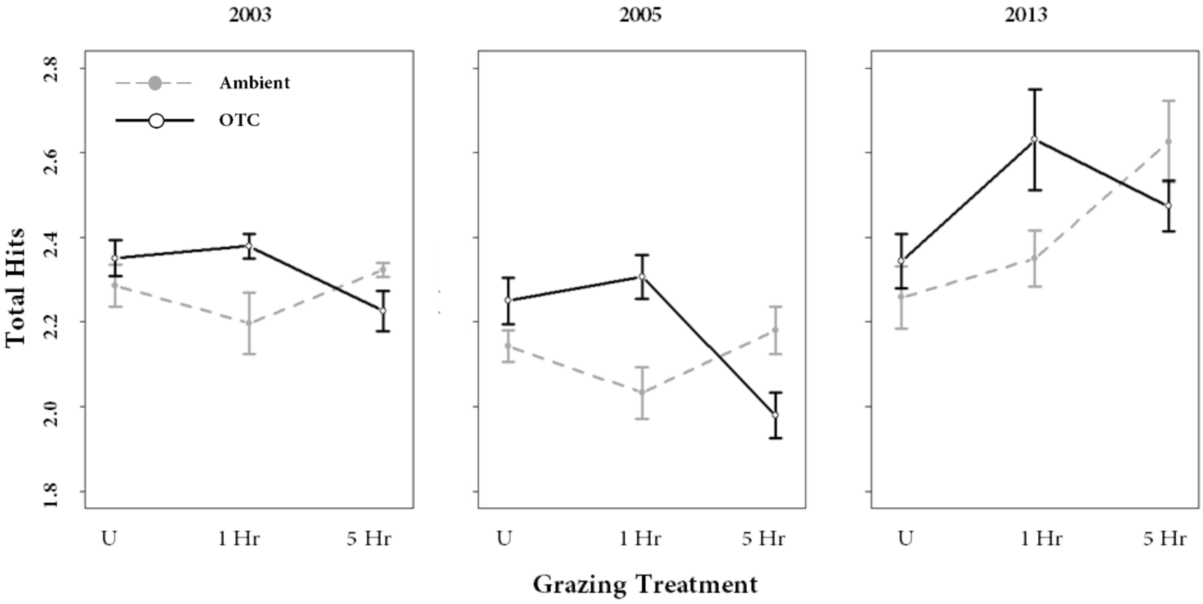

Figure 1. Total hits during the years 2003, 2005 and 2013, 8 years since the last grazing treatment. The values displayed are log transformed and show standard error of the mean. (U=ungrazed; 1 Hr = 1 hour grazed; 5 Hr = 5 hours grazed). n=5

4.2 COMMUNITY COMPOSITION – SPECIES LIST

Table 6 in Appendix shows the presence and absence of plant species hit derived from hit data in 2013. Grasses, sedges, pteridophytes, forbs and bryophytes are ubiquitous in all plots. Plots are dominated by the following species within those functional groups: *Dupontia* sp., *Calamagrostis stricta* (grasses), *Eriophorum scheuchzeri* (sedge), *Cardamine nymanii* (forb), *Equisetum arvense* (pteridophyte), *Calliergon richardsonii, Aulocomnium palustre, Drepanocladus revolvens, Paludella squarrosa,* and *Pohlia cruda* (bryophytes). *Salix polaris, Carex subspathacea, Ranunculus hyperboreus, Aulocomnium turgidum, Mnium blytti,* and *Liverwort* sp. were found only in OTC plots. *Koenigia islandica* was not found in 5 hr grazed plots of both ambient and OTC.

Comparing the species presence and absence in 2013 (Table 6 in Appendix) to 2003 and 2005 (Table 7 and Table 8 in Appendix), changes in species occurrence have occurred. *Sphagnum* sp was found in abundance in 2003 and 2005, but has disappeared from all plots in 2013. It was not found in the surrounding area for the duration of the fieldwork. *Cerastium regelii* was present in all treatments in 2003 and 2005, but was never hit in 2013. *Poa sp., Cochlearia groenlandica, Saxifraga* sp., *Bryum* sp., or *Stereocaulon* sp. were also no longer found, and *Salix polaris* was found in only the 1 hr and 5 hr gazed plots of OTCs. *Paludella squarrosa* and *Pohlia cruda* were ubiquitous in 2013, in comparison to rarely being found in 2003 and 2005. *Carex glareosa* had not been found in 2003 or 2005, but was present in all treatments except for 1 hr ambient. The rush, *Juncus* sp., was only found once in 2005 in an ungrazed OTC plot. There doesn’t appear to be a pattern for *Bistorta vivipara* across years. *Koenigia islandica* had been present in all treatments in 2003 and 2005, but was no longer hit in 5 hr grazed plots of both ambient and OTC in 2013. *Ranunculus pygmaeus* was no longer found in 2005 and 2013, and *Ranunculus hyperboreus* changed from being hit in all treatments except ungrazed ambient in 2003, to hit in all treatments except 5 hr grazed, to being only found in a 1hr grazed OTC plot in 2013. *Mnium blytti* was not present in 2003, but was hit in all treatments except for 5 hr grazed ambient and ungrazed OTC in 2005, to only being hit in OTC treatments in 2013. *Meesia triquestris* was only found in 2013, where it was hit in all treatments except ungrazed ambient. *Polytrichum* sp. was not found in 2003 and 2005, except for in 1 hr grazed ambient in 2005. By 2013, it was found in all except 1 hr grazed ambient and ungrazed OTC. *Sanionia uncinata* remained relatively unchanged across years. *Liverwort* sp. was only found in 2013 OTC treatments.

Dupontia sp., *Eriophorum scheuchzeri, Cardamine nymanii, Equisetum arvense,* and *Calliergon richardsonii* have remained present in all treatments in all years.

4.3 COMMUNITY COMPOSITION – FUNCTIONAL GROUPS

Figure 2 displays the log transformed total hits of the Pteridophyte *Equisetum arvense* with standard error bars for all treatments in 2003, 2005 and 2013. Block was estimated as a random factor and data fitted to a linear mixed model with ungrazed ambient plots as the intercept (Effect sizes and output from fit displayed in Table 11 in Appendix).

In 2003, an analysis of variance showed grazing the significant main effect (F-value=12.881, *p*-value<0.001) with no interaction. Tukey's post hoc test 5 hour grazed plots showed significantly decreased total hits compared to ungrazed in both ambient and OTC (*p*-value<0.001). Differences between 1 hour grazed and 5 hr grazed bordered as insignificant (*p*-value=0.058), and no effect of OTC was found at all grazing levels.

In 2005, an analysis of variance showed neither warming or grazing as significant main effects, but the interaction was significant (F-value=8.386, *p*-value=0.002). Testing the interaction showed total hits in 1 hr OTC were higher than in ambient (*p*<0001).

In 2013, warming had a significant overall effect (ANOVA F-value=12.260, *p*-value=0.002) and no interaction. Tukey's post hoc analysis shows OTC plots had higher hits than ambient in all grazing levels (*p*-value=0.033).

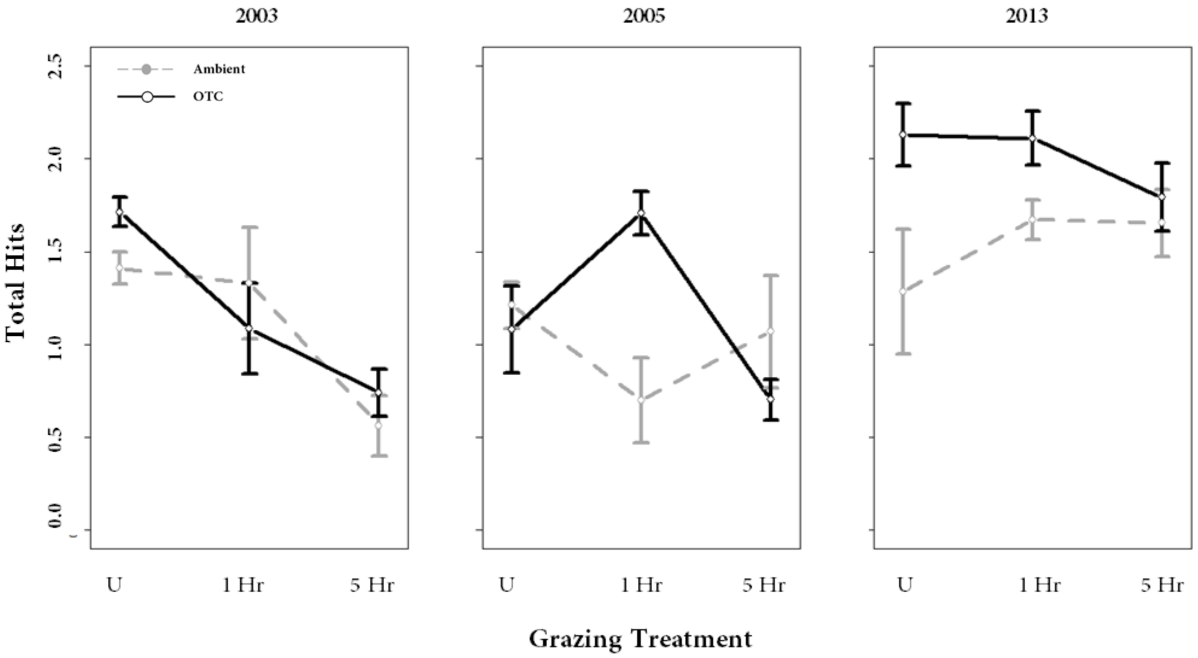

Figure 2. Total hits of the Pteridophyte *Equisetum arvense*; the only horsetail dominating the wet tundra FRAGILE site on Svalbard. Data is $\log_{10}$ transformed and shows changes over ten years of warming, and grazing pressure applied in 2003, 2004 and 2005. Standard error bars are shown. (U=ungrazed; 1 Hr = 1 hour grazed; 5 Hr = 5 hours grazed). n=5

Figure 3 displays the log transformed total hits of the graminoids with standard error bars for all treatments in 2003, 2005 and 2013. Block was estimated as a random factor and data fitted to a linear mixed model with ungrazed ambient plots as the intercept (Effect sizes and output from fit displayed in Table 12 in Appendix).

In 2003, analysis of variance showed grazing was the main effect (F-value=3.496, *p*-value=0.050), although this should be interpreted with care, and no interaction. Total hits in 1 hr ambient treatment were higher than ungrazed ambient (t-value=2.607, *p*=0.016). According to Tukey's test, no significant differences were found between warming and grazing treatments.

In 2005, analysis of variance showed grazing was the main effect (F-value=5.763, *p*-value=0.011) with no interaction. Total hits in 1 hr ambient treatment were higher than ungrazed ambient (t-value=2.077, *p*=0.050). According to Tukey's test, no significant differences were found between warming and grazing treatments**.**

In 2013, analysis of variance showed warming as the main effect (F-value=20.482, *p*-value<0001) with no interaction. According to Tukey's post hoc test OTC plots had higher hits than ambient across all grazing levels (*p*-value=0.002).

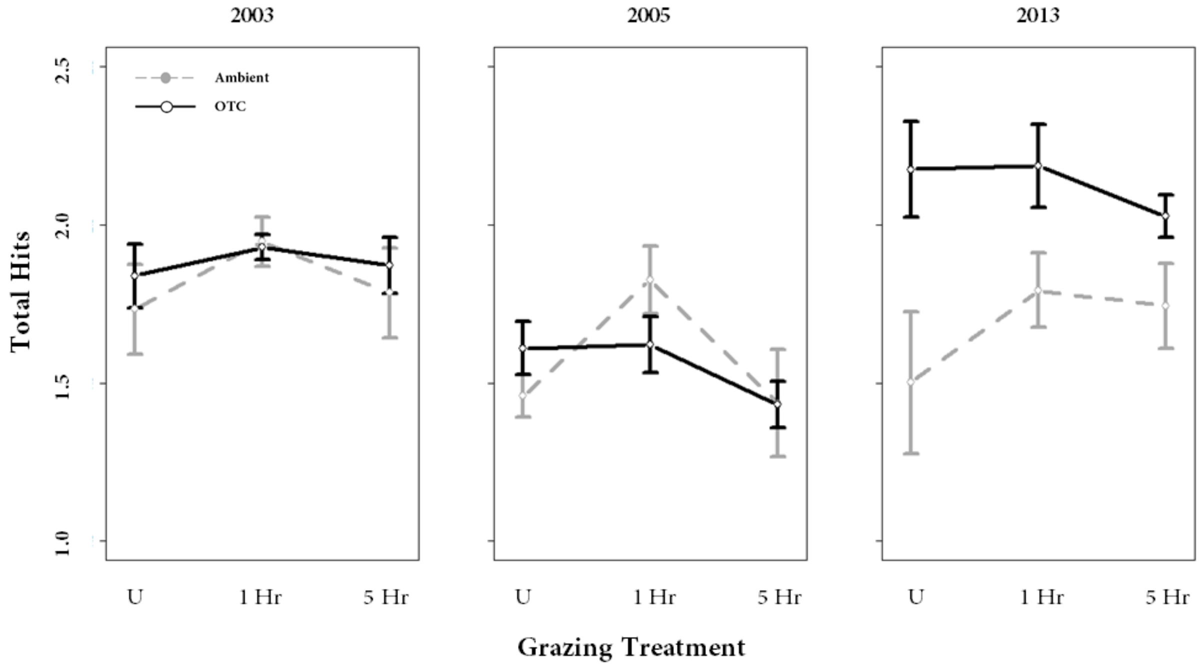

Figure 3. Total hits of graminoids (*Calamagrostis stricta*, *Dupontia* sp., *Poa* sp., *Poa vivipara*, and *Poa arctica* [grasses], *Carex subspathacea*, *Carex glareosa*, *Eriophorum scheuchzeri* [sedges], and *Juncus* sp. [rush]) in the wet tundra FRAGILE site on Svalbard. Data is $\log_{10}$ transformed and shows changes over ten years of warming, and grazing pressure applied in 2003, 2004 and 2005. Standard error bars are shown. (U=ungrazed; 1 Hr = 1 hour grazed; 5 Hr = 5 hours grazed). n=5

Figure 4 displays the log transformed total hits of the forbs with standard error bars for all treatments in 2003, 2005 and 2013. Block was estimated as a random factor and data fitted to a linear mixed model with ungrazed ambient plots as the intercept (Effect sizes and output from fit displayed in Table 13). No significant effects were found in all years.

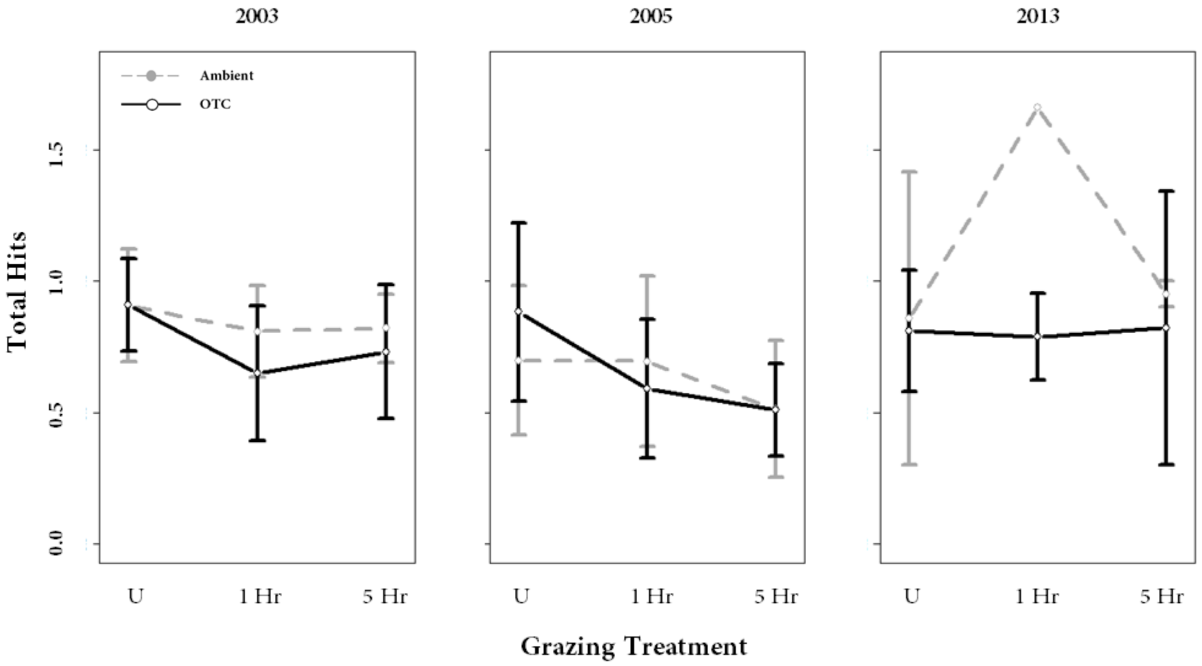

Figure 4. Total hits of forbs (*Bistorta vivipara, Cardamine nymanii, Cochlearia groenlandica, Cerastium regelii, Koenigia islandica, Ranunculus hyper boreus, Ranunculus pygmaeus, Saxifraga cernua, Saxifraga hieracifolia, Saxifraga foliolosa, Saxifraga tenuis, Stellaria crassipes*)in the wet tundra FRAGILE site on Svalbard. Data is $\log_{10}$ transformed and shows changes over ten years of warming, and grazing pressure applied in 2003, 2004 and 2005. Standard error bars are shown except for the data point 1 Hr OTC in 2013 because only one plot contained forbs. (U=ungrazed; 1 Hr = 1 hour grazed; 5 Hr = 5 hours grazed). n=5

Figure 5 displays the log transformed total hits of the bryophytes with standard error bars for all treatments in 2003, 2005 and 2013. Block was estimated as a random factor and data fitted to a linear mixed model with ungrazed ambient plots as the intercept (Output from fit displayed in Table 14).

In 2003, an analysis of variance showed grazing as the main effect (F-value=13.310, *p*-value<0.001) with no interaction. The additive model showed decreased total hits in 1 hour grazed ambient plots compared to ungrazed ambient (t-value=2.550, *p*-value=0.019). Tukey's post hoc analysis shows no significant difference between ungrazed and 1 hour grazed in both OTC and ambient.

In 2005, an analysis of variance showed grazing as a main effect (F-value=5.764, *p*-value=0.011) with no significant interaction with warming. Tukey's post hoc analysis of the additive linear mixed model means showed 5 hour grazed hits as significantly lower than ungrazed and 1 h grazed for both OTC (*p*-value=0.018) and ambient (*p*-value<0.001). OTCs were not significantly different from ambient for all grazing treatments, and there was no significant difference between ungrazed and 1 hour grazed.

In 2013, analysis of variance showed warming as the main effect (F-value=4.577, *p*-value=0.044) with no interaction. An additive model was fit, and ungrazed OTC plots had higher hits than ungrazed ambient (t-value=2.139, *p*-value=0.044). No significant differences were found with Tukey's post hoc analysis.

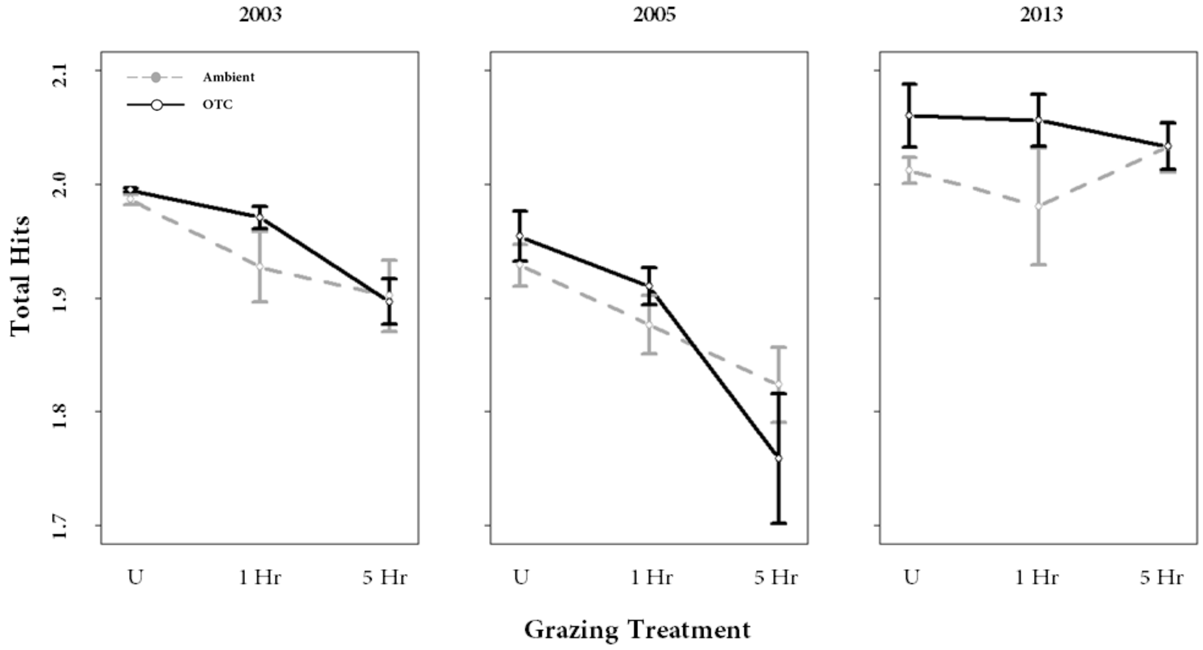

Figure 5. Total hits of Bryophytes (*Aulocomnium palustre, Aulocomnium turgidum, Bryum* sp., *Calliergon richardsonii, Drepanocladus revolvens*, *Mnium blytti*, *Meesia triquestris*, *Paludella squarossa, Pohlia cruda, Polytrichum* sp., *Sanionia uncinata*, *Sphagnum* sp.) in the wet tundra FRAGILE site on Svalbard. Data is $\log_{10}$ transformed and shows changes over ten years of warming, and grazing pressure applied in 2003, 2004 and 2005. Standard error bars are shown. (U=ungrazed; 1 Hr = 1 hour grazed; 5 Hr = 5 hours grazed). n=5

4.4 EMPIRICAL DATA –SINKING OF OTCS, MOSS DEPTHS AND HYDROLOGY

The OTCs have not been removed between the year 2005 and 2013, and have sunk into the tundra moss layer. OTCs in block WB sank the least, with an average of 6.9 cm (SD=5.1) and those in block WC sank the most to an average depth of 18.9 cm (SD=3.0) from the top of the moss layer. Table 3 in the Appendix shows the average depth and standard deviation of sinking in each block. Block WD is not shown because measurements were not performed on that block.

Moss and water level depth varied between blocks as well, with WC containing the thickest layer of moss and most water, and Table 4 and 5 in the appendix show the average thickness of moss layer and water depth in the plots of each block.

4.5 TEMPERATURE DATA

Temperature sums were higher in the air and lower in the soils of the OTCs compared to ambient in both 2013 and 2003. (Table 1).

Table 1. Temperature Sums (°C) and OTC effects for 6-26 July 2003 (from Cooper et al. 2006) and July 6–August 28 2013 for both 5 hour grazed (n=3) and ungrazed (n=5) treatments. Tinytag loggers (Gemini, UK) recorded temperature every hour in 2003 and every half hour in 2013. 20 days of data are included in 2003, and 53 days in 2013. Below ground loggers in 2013 were placed at average depth 7.4cm and surface loggers at average height 9.4cm.

Year	Logger	Ambient	OTC	OTC - Ambient
2003	Air	202	216	+14
	Soil	121	115	-6
2013	Air	3310	3480	+170
	Soil	2724	2685	-39

Table 2 summarizes the temperature sums in 2013 further sorted into ungrazed and 5 hour grazed plots. Higher temperature sums where found in both air and soil of the ungrazed OTC plots compared to ambient. In 5 hour plots, sums were higher for air but lower for soil of OTC plots compared to ambient. See Table 2 in Appendix for locations of loggers in blocks of the field site.

Table 2. Temperature sums (°C) for July 6 – August 28 2013 of ungrazed (n=5) and 5 hour grazed (n=3) treatments. Tinytag loggers (Gemini, UK) recorded temperature every hour in 2003 and every half hour in 2013. Below ground loggers were placed at average depth 7.4cm and surface loggers at average height 9.4cm. Raw data for 2003 in the context of grazing treatment was not available for analysis.

Year	**Grazing**	**Logger**	**Ambient**	**OTC**	**OTC - Ambient**
2013	Ungrazed	Air	2344	2430	+86
		Soil	2000	2155	+155
	5 hour	Air	1363	1483	+120
		Soil	1096	890	-206

Mean daily temperatures were consistently higher in OTCs compared to ambient for air loggers for the entire field season (June 11th – August 28th), although this was not statistically significant (t=-1.3872, p=0.1674). Soil loggers in OTCs consistently recorded higher daily average temperature compared to ambient in June and beginning of July, lower for the rest of July and nearly equivalent in August (Figure 6). The temperature of the soil in OTCs were not significantly different from ambient (Kruskal-Wallis chi-squared=78, p=0.4787). The air temperature was higher than soil temperatures for most of the season (Wilcoxon signed-rank test V = 99, p-value < 2.2e-16).

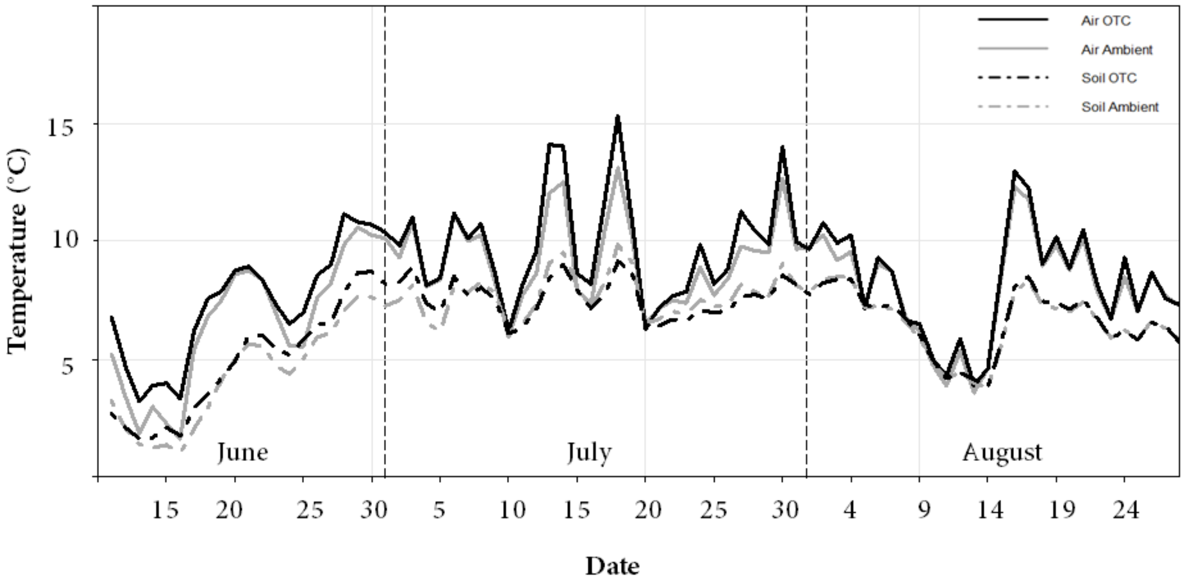

Figure 6. Mean daily temperatures from June 11th – August 28th 2013. Data is from the wet site of the FRAGILE experiment, averaged across all replicate loggers within each treatment combination, and includes and each treatment combination is composed of ungrazed (n=3) and 5 hour ungrazed treatment (n=5).

Table 3 shows mean monthly temperatures grouped by warming treatment and placement within the plot. Mean temperature was highest in July, lowest in June and intermediate in August. They were higher in OTC plots compared to ambient for both air and soil loggers, except for the soil loggers in July.

Table 3. Mean monthly temperatures and standard deviation from June 11th – August 28th 2013. Calculated from raw temperature data in wet tundra FRAGILE site and averaged across replicate data loggers within each treatment combination, includes and each treatment combination is composed of ungrazed (n=3) and 5 hour ungrazed treatment (n=5).

Logger	**Treatment**	**June**	**July**	**August**
Air	Ambient	6.4 [3.6]	9.2 [3.9]	8.0 [3.1]
	OTC	7.2 [4.3]	9.9 [4.3]	8.2 [3.5]
Soil	Ambient	4.2 [2.8]	7.7 [2.4]	6.5 [1.7]
	OTC	4.8 [3.2]	7.6 [3.0]	6.6 [2.1]

Figure 7 displays the 24 hour diurnal temperature patterns for the middle two weeks in June, July and August 2013 (11th-24th, 9th- 22nd, and 8th-21st respectively). Temperatures were higher for air compared to soil (V = 10287, p-value < 2.2e-16), although approached equivalent minimums around midnight only in July and August. Both soil (V = 1690, p-value = 0.0351) and air (V = 2497, p-value = 3.227e-11) temperatures were higher in OTCs compared to ambient plots, except for soil loggers in the month of July. (Figure 2)

Table 8 in the appendix summarizes the ranges and time of reading for the diurnal temperature shown in Figure 2. 24 hour diurnal temperature data shows peaking of air temperature in ambient and OTC plots the earliest July at 11:00, latest in June at 13:00 and intermediate in August at 12:00. The minimum temperatures are reached at different times; around 01:00 for air and a lag of several hours between 02:00 and 05:00 for soil.

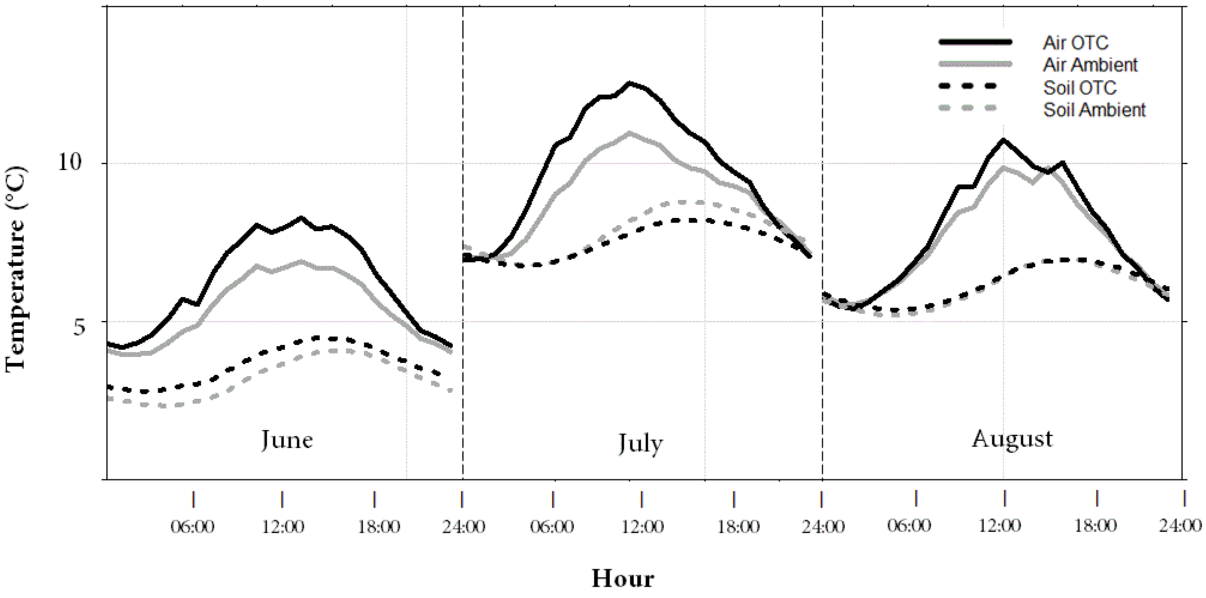

Figure 7. 24 hour diurnal temperature from the middle two weeks in June, July and August (June 11th-24th, July 9th- 22nd, and August 8th-21st) in wet tundra of the FRAGILE site in 2013.

5 Discussion

This experiment has provided some insight into the response of wet Arctic tundra to higher goose grazing disturbance and manipulated temperature increase at a longer time scale. The results show that such time-scales are necessary to clarify responses of biomass and plant communities. Furthermore, the use of OTCs in wetlands as a warming device works for air temperature but can decrease soil temperature in wet habitats.

5.1 TOTAL HITS – DELAYED RECOVERY IN TERMS OF ABOVE GROUND BIOMASS

Total hits were used as a non-destructive proxy for biomass (Redjadj et al. 2013; Godìnez-Alvarez et al. 2009; Jonasson 1988), where recovery from grazing was defined as comparable biomass of ungrazed control treatment. The response of above ground biomass to natural levels of grazing simulated in the 1 hour grazing treatment revealed complete recovery 8 years after termination of grazing treatment in ambient temperature conditions. The 1 hour treatment is of interest due to the expectation for compensatory growth due to ambient levels of grazing (McNaughton 1979; Van der Graaf et al. 2006), which our results show did not occur. Biomass had decreased in 2005, likely due to insufficient nutrient deposits in the faeces of geese (Pouliot et al. 2009), and this decrease has been found before in a short-term clipping experiment on Ellesmere Island (Elliot and Henry 2011). This was no longer detected in 2013. On the other hand, biomass responded positively in the 5 hour treatment in 2013, which was simulating the impact of grazing disturbance caused by substantial population increases of barnacle geese. This is likely due to three years of intensive grazing, when the inefficient digestive track of the geese deposited nutrient rich faeces (Van der Wal and Loonen 1998; Gauthier et al. 2006; Gornall et al. 2009) that would be taken up mostly by the moss layer (Pouliot et al. 2009), but vascular plants as well as sufficient nutrients were deposited.

When considering the response of biomass to the impact of warming by OTCs, the substantial increase in above ground biomass due to climate warming found in other parts of the Arctic (Gauthier et al. 2013; Hudson et al. 2009; Hill and Henry 2011; Tape et al. 2006) did not occur to a great extent in this field site. A substantial community wide response to warming may only occur in decadal time scales (Hudson and Henry 2009), as short-term responses at a community level have been small in some cases under 10 years of study (Hollister and Flaherty 2010). The interaction between warming and grazing revealed that biomass responded positively to 1 hour grazing in OTCs 8 years after termination of grazing treatment, and remained consistently higher in OTC than ambient in previous years as well. This positive response was dampened in 5 hour grazing treatment, suggesting that the higher grazing pressure prevented the OTCs from substantially increasing above ground biomass.

5.2 COMMUNITY COMPOSITION – CHANGES AT THE SPECIES LEVEL

Growth response and community shifts are expected to be species specific (Doreepal 2007) and influenced by a combination of herbivore selective grazing, warming, grazing and other indirect effects, and some will not respond at all (Elmendorf et al. 2012b; Kuijper and Bakker 2005; Madsen et al. 2011; Post and Pedersen 2008). Furthermore, removal of grazers has led to large changes in salt marsh communities (Bazely and Jefferies 1986; Hik et al. 1992), suggesting barnacle geese act to stabilize community changes. A similar experiment was conducted in Greenland where plots were exposed to 7 years of warming and herbivore removal. A reduction of species diversity and stability of the plant community was found, suggesting that grazing by geese maintains community composition (Post 2013). In this experiment the dominant species, which were also preferred forage species, have remained present in all treatments. Notable changes include the disappearance in 2013 of most forbs, the moss *Sphagnum* sp and *Bryum* sp, the grass *Poa* sp, as well as the appearance of the mosses *Meesia triquestris*, *Polytrichum* sp, *Paludella squarrosa*, and *Pohlia cruda* and a species of liverwort. The disappearance of *Poa* sp could be due to error by the observer, as the ability to differentiate *Poa* sp and *Dupontia* sp was questionable by the end of the growing season. The complete disappearance of *Koenigia islandica*, the only annual plant on Svalbard, in 5 hour grazed treatments suggests the species did not recover from high grazing pressure. This may not be surprising considering the need for a complete life cycle within one short growing season, despite its adaptations to Arctic conditions (Heide and Gauslaa 1999; Wagner and Simons 2009). The appearance of other species of moss, and disappearance of *Sphagnum* sp is in contrast to the negative response of moss diversity to warming, and the notable resistance of response in *Sphagnum* sp to warming in wet conditions (Gunnarsson 2005; Lang et al. 2009; Lang et al. 2012). Although geese will selectively graze flowers and buds of forbs and grasses (Alsos et al. 1998), their faeces have been shown to contain large numbers of viable seeds from their preferred forage species, suggesting the possibility of influence on species richness of foraged communities (Bruun et al. 2008), even though it’s been found they reduce the soil seed bank (Kuijper et al. 2006). The changes found by 2013 are a complex mix of species specific responses to grazing and warming, with most changes occurring with rare species.

5.3 COMMUNITY COMPOSITION – CHANGES AT THE FUNCTIONAL GROUP LEVEL

The responses of functional groups were expected to differ due to the complex interaction between nutrient deposition by geese in the initial experiment, trampling, and species specific responses to warming. Nutrient subsidies from feces deposited by geese typically act to bolster the response to more intense grazing by freeing the plants from nutrient limitations typical of tundra soils (Bokhorst et al. 2007b). In thick moss, this nutrient input is taken up entirely by moss and only reaches graminoids to effect heir growth when deposition is high (Pouliot 2009). The over compensatory response may only work in the short term, with recovery in the long term reflective of the cooler soils and poor nutrient cycling in wet tundra. This interacts with the trampling by geese, which was substantial in the case of 5 hour treatment.

In this case, assessing the responses by functional group classification was quite simple. The field site was dominated by two particular groups of interest; one species of pteridophyte *Equisetum* arvense and graminoids. Few studies are available for *Equisetum* arvense, but one precious study on its close relative *Equisetum fluvialis* found a substantial short-term positive response to warming (Ojala et al. 2001). It is a preferred species for foraging by barnacle geese, yet by 2013, no effect of grazing was detected and enhanced response to warming was seen across all grazing levels; suggesting that the on pteridophyte had recovered fully from grazing, and continued to respond positively to warming by producing more aboveground biomass. The similar response by graminoids suggests that the positive response to grazing in moss dominated habitats (Van der Wal and Brooker 2004) may be a short-term effect, both graminoids and pteridophytes respond positively to warming over a longer time scale of 8 years continuous warming. A similar response was found in the Canadian Arctic after over 24 years of monitoring (Gauthier et al. 2013; Hill and Henry 2011). Since graminoids represent over 90% of biomass in wet tundra in the Canadian Arctic (Gauthier et al. 1995), such growth responses are likely to be considerable at a circumpolar scale.

The effect of grazing and warming on forbs was not detected, likely due to extreme rarity of this functional group. For example, in 2013, only one specimen was hit in the 1 hour ambient treatment, hence the lack of error bars. Changes in species hits in Table 6-8 in the Appendix shows that numerous species have completely disappeared by 2013. Clearly, a factor in the site has prevented forbs from re-establishing after the disturbance. As a preferred forage species by geese, the increased rarity over time is surprising since goose feces also contain high numbers of plant propagules of their preferred forage plants. After three summers of grazing and 8 years of grazing inhibition, seeds deposited in feces would be a method of re-establishment (Bruun et al 2008). Furthermore, forbs have been shown to respond positively in the long-term to warming (Hill and Henry 2011). Soil temperatures may be a factor in this case, for example the forb *Cardamine nymanii* has been shown to decrease in biomass by 50% in chilled soils (Van der Wal et al. 2001). This same cause may have negative repercussion on the forbs that have disappeared from the experimental plots.

In the functional group bryophytes, the impact of warming only became significant in ungrazed treatments after 10 years, when the impact of grazing was no longer distinguishable. This suggests that prior grazing, although no longer visible in terms of total hits, reduced its ability to respond to warming in later years. The complete recovery of moss from grazing has been documented in other long term studies, as well as little to no response to warming (Van der Wal et al. 2001). Warming can result in quite mixed changes of diversity, with *Sphagnum* sp showing resilience to warming when other species generally do not find it favourable (Lang et al. 2012). In general, moss communities can be considered robust to change and quick to recover from physical disturbances.

5.4 OTCS- USE AS WARMING DEVICES IN ARCTIC WETLANDS

Mimicking the projected increase in temperature is not simple, and the use of OTCs includes numerous confounding effects such as lower wind speed, reduced humidity, temperature extremes and cooling of soils (Marion et al. 1997; Cooper et al. 2004; Hollister et al. 2006; Bokhorst et al. 2013). Warming was achieved in the air with expected diurnal patterns, but soils were cooled in OTC treatments. This has been previously found in this project (Cooper et al. 2004), other studies in the Arctic (Marion et al. 1997; Walker et al. 1999; Jónsdóttir et al. 2005) and boreal forest (Dabros 2010), as well as no change in soil temperature in the long-term natural study on Bylot Island (Gauthier et al. 2013). Water logged soil may be part of the explanation, as the field site received an exceptional amount of rainfall and most of the plots remained saturated for the entire season. This is not a clear explanation, as water diffuses heat more efficiently than air (Rosenberg et al. 1983). Soil warming in wetter areas has also been found in other studies (Hollister et al. 1998).

This complicates our understanding of the warming potential when using OTCs. First, we must ask whether the cooling is as a result of melt water flowing through the site, which may not allow for soils to warm sufficiently. There was no way to tell whether water flowed within the OTC plots, although moving water was clearly observed around them and some plots contained completely submerged vegetation. It is worth noting that the OTCs have not been removed from the plots, and have thus sunk into the moss layer (Table 3 in Appendix). This could force them to function as a cold water trap, with sufficient input from the outside to keep the soils cooled but not enough for this to be obvious to observers. OTCs normally function well in mesic habitats, where they are raised slightly above ground level to allow for air flow.

The cooling of the soil could be due to a combination of incoming solar radiation and the residual impact of grazing on moss layer thickness. Temperatures were higher in the soil of OTCs in June, when the sun is at its peak. OTC have been shown to warm mostly due to PAR levels (Bokhorst et al 2013), which would be maximal at that time in the season. However, lower temperature sums were found in 5 hr grazed treatments, not in ungrazed. This resembles the results of Van der Wal et al. (2001), where the exclusion of grazers for 7 years caused an increase in the thickness of the moss layer and reduction of soil temperatures by 0.9°C. The study design of the FRAGILE experiment essentially also inhibits further grazing by geese and reindeer within OTC plots. Further research can be done on this topic on this site to clarify this point. The change from warming to cooling of soils in July and August are likely due to rapidly decreasing PAR levels.

The cooling of soil is expected to have negative repercussions on the response of plants growing within the moss layer. A moss layer, characteristic of wet sites, has a significant negative influence on the nutrient availability and soil temperature by acting as an insulator, thereby influencing the energy transfer, microbial activity and nutrient cycling of arctic tundra (Gornall et al. 2007; Van der Wal 2001). This can directly affect biomass, for example the 50% reduction of *Poa* arctic and *Cardamine* nymanii in soils cooled by a thickened moss layer of the herbivore exclusion experiment (Van der Wal 2001). It could work against the positive influence of warming by OTCs on soil processes, which can require significant warming to become effective (Bokhorst et al. 2007a). A potentially negative effect of cooler soils may not be surprising, as warmed soils have been shown to increase growth response to different extents in High Arctic non-graminoids, sedges and rushes and most by graminoids (Brooker and Van der Wal 2003).

As for weaknesses in experimental design, there are too few replicates (n=5). Also, the hydrological conditions (Table 5 in the Appendix) differ greatly between blocks, with clear effects on the studied characteristics of plant communities in the plots. It was for this reason mixed models were used, as using blocks as a random factor should account for this variation. According to the model used, block accounted for as much as 5% to 68% of the variation measured, making important to analyse. Further analysis of the data could incorporate block as a fixed factor, to see if soil saturation is a potential gradient. The use of classical hypothesis testing with two way ANOVA was permissible in this case largely due to the balanced design of the experiment, but more information can be gleaned by analysing over the three years of data available. Furthermore, complex analysis is needed for further perusal of community data. There are powerful statistical tools available in the software R (Oksanen 2013) to use ordination, a group of techniques frequently used by plant ecologists to visualize changes in species composition in plant communities.

5.5 THE IMPORTANCE OF LONG TERM STUDIES

Detailed knowledge of the repercussions of higher grazing pressure on Arctic tundra is critical for the ongoing management of the migrating goose populations of barnacle geese. The majority of supporting literature address short term effects, but miss out on numerous examples of delayed responses anywhere from 4 years to over a decade (Callaghan 2013; Gauthier et al. 2013; Groffman et al. 2006; Walther 2010; Wiederman et al. 2007) and the spatial and temporal heterogeneity between years (Hollister et al. 2005a; Madsen et al. 2011; Gauthier et al. 2013; Magurran et al. 2010) in the few long-term studies available. These highlight the importance of capturing the full complexity of recovery in the Arctic over longer temporal scales in ecology studies (Herrick et al. 2006; Turner et al. 2003), albeit not well supported by current academic resources. Considering the importance of Arctic feeding grounds in terms of adult goose body condition and breeding success (Hahn et al. 2011; Verhoeven et al. 2006), addressing long-term recovery in wet Arctic tundra feeding grounds in the context of climate change will allow for finer management of goose populations. If changing climate conditions adversely affects the preferred forage species or reduces the amount of biomass available for consumption, a negative effect on goose populations would be predicted.

5.6 CONCLUSION

I have shown that the long term recovery potential of wet Arctic tundra due to goose grazing is incomplete eight years after intense disturbance, and interacts with the effects of warming climate conditions. This results in species and functional group specific responses, unique to the foraging preferences of the responsible herbivore barnacle geese and wet conditions of their preferred habitat. The results must be interpreted knowing the weakness of the experiments methods; in this case the cooling of soils by OTCs in wet habitats. Future research with the purpose of management must take into account the variability in response over longer time scale, which would provide much clearer information about the ability of Arctic tundra to respond to any number of disturbances.

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7 Appendix

7.1 FIGURES

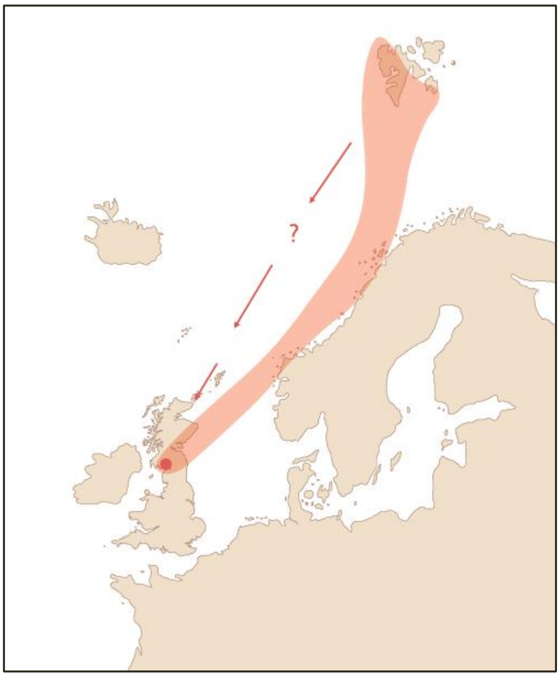

Figure 1. Wintering, spring staging, migration and breeding locations of the Svalbard Barnacle Geese (*Branta leucopsis*, red). Geese overwinter in the UK, stage on mainland sites in Norway and breed in summer on Svalbard. Some fly nonstop from the UK to Svalbard. Figure replicated from O'Connell et al 2006 and modified to show only *Branta leucopsis*.

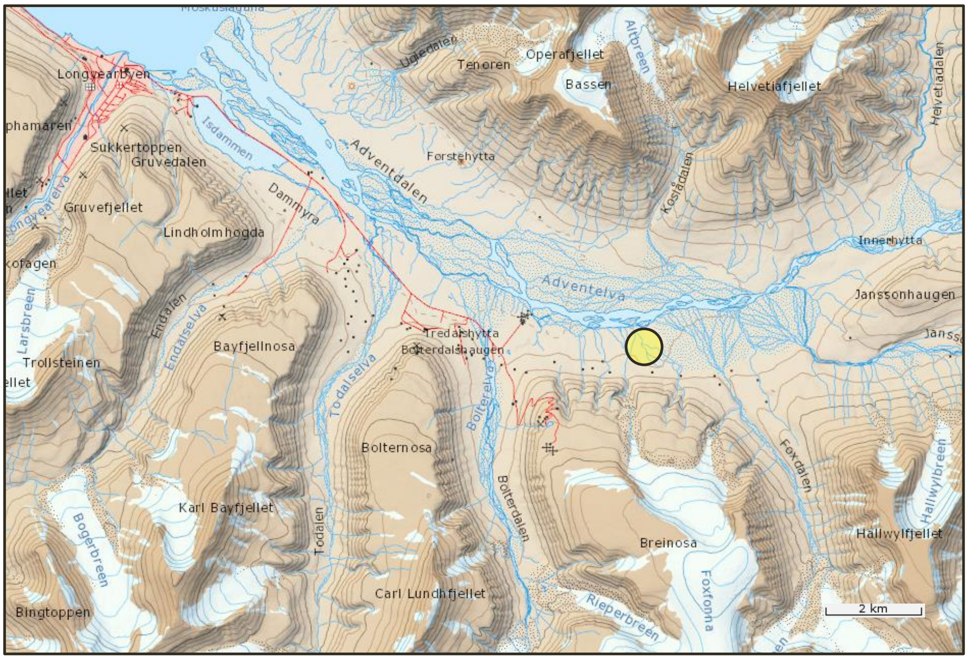

Figure 2. Map of wet field site in Adventdalen, Svalbard (78°N, 16°E). Field site location is marked by a yellow circle (http://www.npolar.no/en/services/maps/).

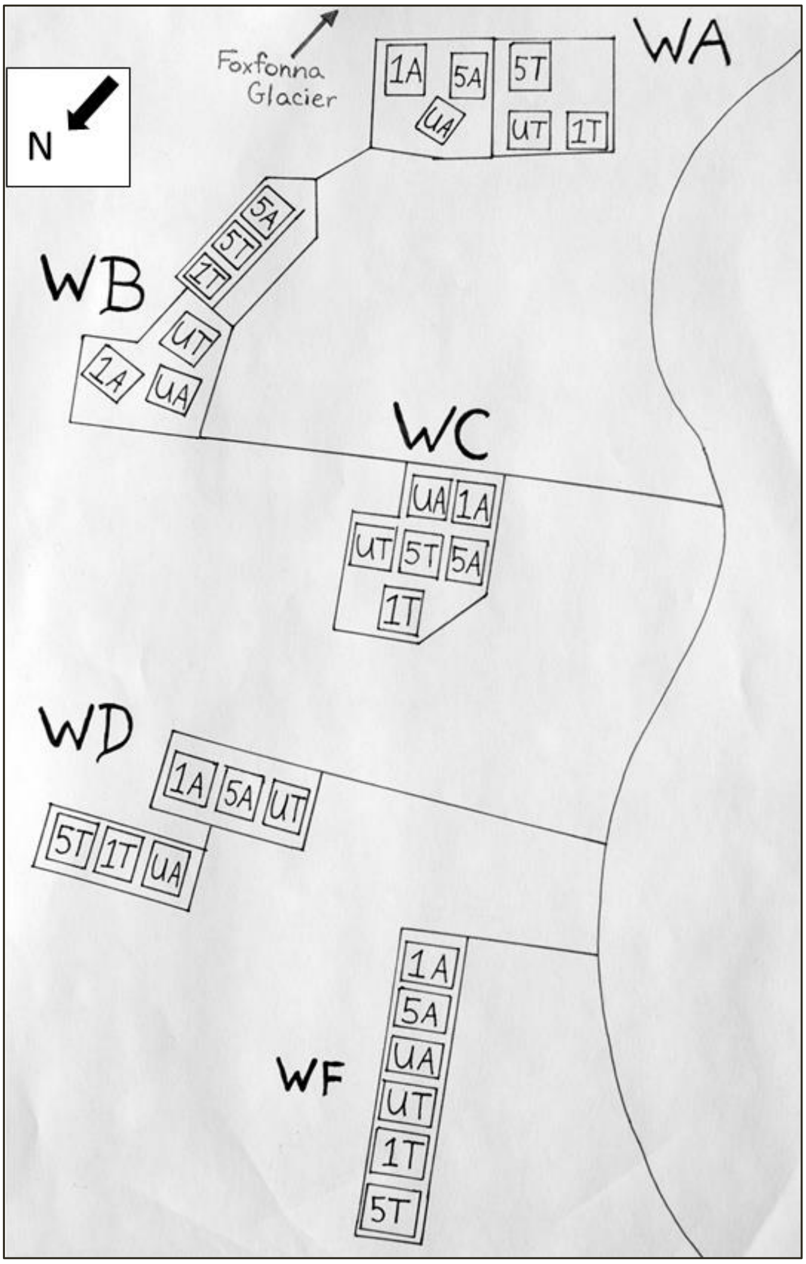

Figure 3. Site map showing locations of blocks WA, WB, WC, WD and WF. Within each block are the treatment combinations (UA) ungrazed ambient, (1A) 1 hour grazed ambient, (5A) 5 hour grazed ambient, (UT) ungrazed OTC, (1T) 1 hour grazed OTC and (5T) 5 hour grazed OTC. The map is not drawn to scale.

Figure 4. Aluminium picture stand (75cm x 75cm plot frame) used to photograph (Nikon 3200) each plot during the period August 7-9.

7.2 TABLES

Table 1. Homogenized mean monthly temperatures (°C) and precipitation (mm) from Svalbard Airport (altitude=28m) from June 1st 2013 to August 31st 2013. Standard error of the mean is shown and calculated from raw data from Eklima.no.

Year	Month	Mean Temperature (°C)	Mean Precipitation (mm)
2003	June	2.8 [0.3]	0.1 [0.1]
	July	6.9 [0.4]	1.4 [0.4]
	August	6.5 [0.4]	0.9 [0.8]
2005	June	4.6 [0.3]	0.2 [0.1]
	July	7.3 [0.3]	1.2 [0.6]
	August	6.8 [0.2]	0.8 [0.2]
2013	June	4.3 [0.5]	0.9 [0.4]
	July	7.4 [0.3]	2.0 [0.6]
	August	7.2 [0.4]	2.2 [0.5]

Table 2. Locations of the 32 loggers installed June 11th (Ungrazed treatments) and July 4th (5 hour treatments). Each treatment contained one soil and one air logger. (U, Ungrazed; 5, 5 hour grazed; A, ambient; T, OTC)

Block	Treatments	Total Loggers Installed
WA	UA, UT, 5A, 5T	8
WB	UA, UT	4
WC	UA, UT	4
WD	UA, UT, 5A, 5T	8
WF	UA, UT, 5A, 5T	8

Table 3. Average depths (cm) OTCs have sunk in the moss layer of wet tundra of the FRAGILE site in 2013.

Block	Average Depth (cm)	Standard deviation
WA	8.0	3.0
WB	6.9	5.1
WC	18.9	3.0
WD	NA	NA
WF	7.3	3.7

Table 4. Average depth and standard deviation ([ ]) of soil/dead moss and live moss layer of all wet site plots in August 2013. (U, Ungrazed; 5, 5 hour grazed; A, ambient; T, OTC)

	Block									
Treatment	**WA**		**WB**		**WC**		**WD**		**WF**	
UA	21.8	1.3	24.9	4.3	41.1	4.6	37.8	1.6	28.1	2.0
	[4.6]	[0.7]	[4.3]	[0.5]	[4.7]	[1.9]	[3.8]	[1.0]	[5.2]	[0.6]
1A	22.6	1.8	28.5	3.4	40.2	4.9	26.1	1.8	26.0	1.5
	[5.5]	[1.0]	[4.9]	[1.3]	[4.9]	[1.2]	[5.1]	[0.5]	[4.7]	[1.2]
5A	25.6	1.2	22.1	1.2	39.3	4.3	30.9	1.8	19.5	2.1
	[3.0]	[0.3]	[7.9]	[0.4	[2.9]	[1.3]	[6.0]	[0.2]	[2.9]	[0.6]
UT	26.1	6.1	26.1	3.0	32.0	4.0	29.7	1.4	28.3	1.8
	[6.1]	[0.4]	[4.3]	[1.0]	[4.5]	[0.7]	[3.6]	[0.4]	[4.5]	[0.3]
1T	26.5	1.1	28.1	0.9	35.4	3.7	32.9	1.4	23.0	1.5
	[1.1]	[0.3]	[4.4]	[0.3]	[3.7]	[0.9]	[2.3]	[0.3]	[3.1]	[0.3]
5T	23.6	1.3	26.7	0.6	38.0	3.8	28.5	0.9	29.8	1.6
	[5.6]	[0.4]	[7.0]	[0.2]	[2.8]	[0.6]	[5.0]	[0.3]	[6.2]	[0.6]

Table 5. Average depth of water in cm and standard deviation within each plot in the five block of wet tundra in the FRAGILE experiment. Values are averaged for the field season of 2013.

	Block				
Treatment	**WA**	**WB**	**WC**	**WD**	**WF**
UA	8.8 [1.8]	24.0 [0.4]	36.8 [1.0]	36.1 [4.0]	22.5 [0.7]
1A	18.6 [0.3]	24.1 [0.8]	32.0 [0.6]	18.1 [0.7]	27.5 [0.9]
5A	21.1 [0.8]	16.5 [1.3]	39.6 [2.5]	21.1 [1.0]	18.5 [1.0]
UT	15.0 [4.7]	24.4 [2.2]	39.6 [3.9]	22.6 [4.8]	23.3 [1.9]
1T	18.9 [4.1]	18.0 [2.9]	40.1 [1.3]	26.7 [1.5]	18.4 [1.3]
5T	15.3 [1.0]	13.5 [1.8]	35.2 [5.6]	20.7 [3.9]	18.6 [1.7]
Average per block	16.3 [4.5]	20.5 [4.6]	37.6 [4.2]	23.9 [6.0]	21.0 [3.4]

Table 6. Presence (+) and absence (-) summary of species in treatment combinations of the wet site in August 2013. Data presented has been exposed to grazing treatment in 2003, 2004 and 2005, and warming since 2003, and originates from point frame hit data. Total presence (+) and absence (-) in each treatment combination are at the bottom of the table. Species that were not present in any treatments are still show, as they may have been present in previous years.

Functional Group	Species	Ambient			OTC		
		Ungrazed	1 Hour	5 Hour	Ungrazed	1 Hour	5 Hour
Dwarf Shrub	*Salix polaris*	-	-	-	-	+	+
Grass	*Calamagrostis stricta*	+	+	+	+	+	+
	Dupontia sp.	+	+	+	+	+	+
	Poa sp.	-	-	-	-	-	-
	Poa vivipara	-	-	-	-	-	-
Sedge	*Carex subspathacea*	-	-	-	-	+	+
	Carex glareosa	+	-	+	+	+	+
	Eriophorum scheuchzeri	+	+	+	+	+	+
Rush	*Juncus* sp.	-	-	-	-	-	-
Forb	*Bistorta vivipara*	-	+	-	-	+	-
	Cardamine nymanii	+	+	+	+	+	+
	Cochlearia groenlandica	-	-	-	-	-	-
	Cerastium regelii	-	-	-	-	-	-
	Koenigia islandica	+	+	-	+	+	-
	Ranunculus hyperboreus	-	-	-	-	+	-
	Ranunculus pygmaeus	-	-	-	-	-	-
	Saxifraga cernua	-	-	-	-	-	-
	Saxifraga hieracifolia	-	-	-	-	-	-
	Saxifraga foliolosa	-	-	-	-	-	-
	Saxifraga tenuis	-	-	-	-	-	-
	Stellaria crassipes	-	-	-	-	-	-
Pteridophyte	*Equisetum arvense*	+	+	+	+	+	+
Bryophyte	*Aulocomnium palustre*	+	+	+	+	+	+
	Aulocomnium turgidum	-	-	-	+	-	+
	Bryum sp.	-	-	-	-	-	-
	Calliergon richardsonii	+	+	+	+	+	+
	Drepanocladus revolvens	+	+	+	+	+	+
	Mnium blytti	-	-	-	+	+	+
	Meesia triquestris	-	+	+	+	+	+
	Paludella squarossa	+	+	+	+	+	+
	Pohlia cruda	+	+	+	+	+	+
	Polytrichum sp.	+	-	+	-	+	+
	Sanionia uncinata	-	+	+	+	+	+
	Sphagnum sp.	-	-	-	-	-	-
Hepatophyte	*Liverwort* sp.	-	-	-	+	+	+
Lichen	*Stereocaulon* sp.	-	-	-	-	-	-
Total	+	13	14	14	17	21	19
	-	23	22	22	19	15	17

Table 7. Species presence (+) and absence (-) summary for all treatment combinations in wet tundra habitat on the FRAGILE site in 2003. The data presented has been exposed to one summer of warming and one application of grazing pressure that year, and originates from point frame hit data. Species that were not present in any treatments are still show, as they may have been present in other years.

Functional Group	**Species**	**Ambient**			**OTC**		
		Ungrazed	**1 Hour**	**5 Hour**	**Ungrazed**	**1 Hour**	**5 Hour**
Dwarf Shrub	***Salix polaris***	-	+	+	+	+	+
Grass	***Calamagrostis stricta***	-	+	+	+	+	+
	***Dupontia* sp.**	+	+	+	+	+	+
	***Poa* sp.**	-	+	+	-	+	+
	Poa arctica	-	-	+	-	+	-
	Poa vivipara	-	-	-	-	-	-
Sedge	***Carex subspathacea***	-	-	-	-	+	-
	Carex glareosa	-	-	-	-	-	-
	Eriophorum scheuchzeri	+	+	+	+	+	+
Rush	***Juncus sp.***	-	-	-	-	-	-
Forb	***Bistorta vivipara***	-	-	+	+	+	-
	Cardamine nymanii	+	+	+	+	+	+
	Cochlearia groenlandica	+	-	-	-	-	-
	Cerastium regelii	+	+	+	+	+	+
	Koenigia islandica	+	+	+	+	+	+
	Ranunculus hyperboreus	-	+	+	+	+	+
	Ranunculus pygmaeus	-	+	-	+	-	-
	Saxifraga cernua	+	+	+	-	+	-
	Saxifraga hieracifolia	-	-	-	+	-	+
	Saxifraga foliolosa	+	+	-	+	-	+
	Saxifraga tenuis	-	-	-	-	-	-
	Stellaria crassipes	-	-	+	-	+	+
Pteridophyte	***Equisetum arvense***	+	+	+	+	+	+
Bryophyte	***Aulocomnium palustre***	-	+	-	+	+	+
	Aulocomnium turgidum	-	+	+	+	+	+
	Bryum sp.	-	-	-	-	+	-
	Calliergon richardsonii	+	+	+	+	+	+
	Drepanocladus revolvens	-	+	+	+	+	-
	Mnium blytti	-	-	-	-	-	-
	Meesia triquestris	-	-	-	-	-	-
	Paludella squarossa	+	-	-	-	-	-
	Phi tom	+	+	+	+	+	+
	Pohlia cruda	-	-	-	-	-	-
	Polytrichum sp.	-	-	-	-	-	-
	Sanionia uncinata	-	+	+	+	+	+
	Sphagnum sp.	+	+	+	+	+	+
Hepatophyte	***Liverwort sp.***	-	-	-	-	-	-
Lichen	***Stereocaulon sp.***	-	+	-	-	-	-
Total	+	14	22	21	21	24	20
	-	24	16	17	17	14	18

Table 8. Species presence (+) and absence (-) summary for all treatment combinations in wet tundra habitat on the FRAGILE site in 2005. The data presented has been exposed to three summers of warming and applications of grazing pressure (2003, 2004 and 2005),and originates from point frame hit data. Species that were not present in any treatments are still show, as they may have been present in other years.

Functional Group	**Species**	**Ambient**			**OTC**		
		Ungrazed	**1 Hour**	**5 Hour**	**Ungrazed**	**1 Hour**	**5 Hour**
Dwarf Shrub	*Salix polaris*	-	-	+	+	+	-
Grass	*Calamagrostis stricta*	-	+	+	+	+	+
	Dupontia sp.	+	+	+	+	+	+
	Poa sp.	-	-	-	-	-	-
	Poa arctica	-	-	-	-	-	-
	Poa vivipara	-	-	-	-	-	-
Sedge	*Carex subspathacea*	+	-	-	+	+	+
	Carex glareosa	-	-	-	-	-	-
	Eriophorum scheuchzeri	+	+	+	+	+	+
Rush	*Juncus sp.*	-	-	-	+	-	-
Forb	*Bistorta vivipara*	-	-	-	+	-	+
	Cardamine nymanii	+	+	+	+	+	+
	Cochlearia groenlandica	+	-	+	-	+	+
	Cerastium regelii	+	+	+	+	+	+
	Koenigia islandica	+	+	+	+	+	+
	Ranunculus hyperboreus	+	+	-	+	+	-
	Ranunculus pygmaeus	-	-	-	-	-	-
	Saxifraga cernua	+	+	+	+	+	-
	Saxifraga hieracifolia	-	-	-	-	-	-
	Saxifraga foliolosa	-	-	-	+	+	-
	Saxifraga tenuis	-	-	-	-	-	-
	Stellaria crassipes	-	+	-	-	-	+
Pteridophyte	*Equisetum arvense*	+	+	+	+	+	+
Bryophyte	*Aulocomnium palustre*	+	-	+	+	+	+
	Aulocomnium turgidum	-	-	-	-	-	-
	Bryum sp.	-	-	-	-	+	-
	Calliergon richardsonii	+	+	+	+	+	+
	Drepanocladus revolvens	-	+	+	+	+	+
	Mnium blytti	+	+	-	-	+	+
	Meesia triquestris	-	-	-	-	-	-
	Paludella squarossa	+	-	-	-	-	-
	Phi tom	+	+	+	+	+	+
	Pohlia cruda	-	-	-	-	-	-
	Polytrichum sp.	-	+	-	-	-	-
	Sanionia uncinata	+	+	+	+	+	+
	Sphagnum sp.	+	+	+	+	+	+
Hepatophyte	*Liverwort sp.*	-	-	-	-	-	-
Lichen	*Stereocaulon sp.*	-	-	+	+	+	-
Total	+	14	22	21	21	24	20
	-	24	16	17	17	14	18

Table 9. Maximum and minimum diurnal temperatures and time of reading for air and soil of ambient and warmed (OTC) plots of wet tundra on Svalbard. Data represents the middle two weeks of each month of fieldwork in 2013(June 11th-24th, July 9th- 22nd, and August 8th-21st).

Treatment	**June**				**July**				**August**			
	Min	**Time**	**Max**	**Time**	**Min**	**Time**	**Max**	**Time**	**Min**	**Time**	**Max**	**Time**
Air OTC	4.20	01:00	8.30	13:00	6.96	00:00	12.57	11:00	5.39	02:00	10.75	12:00
Air Ambient	3.97	02:00	6.90	13:00	7.01	00:00	10.98	11:00	5.53	02:00	9.89	12:00
Soil OTC	2.79	02:00	4.49	14:00	6.76	04:00	8.22	15:00	5.37	05:00	6.98	17:00
Soil Ambient	2.33	04:00	4.08	15:00	6.79	04:00	8.78	15:00	5.21	05:00	6.97	17:00

Table 10. Results from linear mixed model fit for total hit data in the wet tundra FRAGILE site in the years 2003, 2005 and 2013. This summarizes the effects of grazing in the years 2003, 2004 and 2005 and ten years of warming from 2003 to 2013.

Model	Model Terms	Effect Estimate	Std. Error	DF	t-value	P-value
2003 Grazing*Warming+1|block Block accounts for 53% of the variation.	Ungrazed	2.28524	0.04644	10.06200	49.203	2.52e-13 ***
	1 hr grazed	-0.08854	0.04521	19.97200	-1.958	0.0643
	5 hr grazed	0.03774	0.04521	19.97200	0.835	0.4138
	OTC	0.06548	0.04521	19.97200	1.448	0.1631
	1 hr grazed:OTC	0.11696	0.06394	19.97200	1.829	0.0823
	5 hr grazed:OTC	-0.16264	0.06394	19.97200	-2.544	0.0194 *
2005 Grazing*warming+1|block Block account for 51% of the variation	Ungrazed	4.93387	0.12227	10.44100	40.353	8.31e-13 ***
	1 Hr grazed	-0.25438	0.12110	19.99000	-2.101	0.048562 *
	5 Hr grazed	0.08534	0.12110	19.99000	0.705	0.489100
	OTC	0.24620	0.12110	19.99000	2.033	0.055534
	1 hr grazed:otc	0.38605	0.17126	19.99000	2.254	0.035560 *
	5 hr grazed:otc	-0.70780	0.17126	19.99000	-4.133	0.000516 ***
2013 Grazing*Warming+1|block Block accounts for 28% of the variation.	Ungrazed	2.25806	0.08266	19.43600	27.316	< 2e-16 ***
	1 hr grazed	0.09194	0.10348	19.98800	0.888	0.38485
	5 hr grazed	0.36830	0.10348	19.98800	3.559	0.00197 **
	OTC	0.08622	0.10348	19.98800	0.833	0.41458
	1 hr grazed:OTC	0.19466	0.14634	19.98800	1.330	0.19844
	5 hr grazed:OTC	-0.23882	0.14634	19.98800	-1.632	-0.11835

Table 11. Results from linear mixed models for the Pteridophyte *Equisetum arvense* in 2003, 2004 and 2005. Data is from the FRAGILE wet tundra site, summarizing the effects of grazing in the years 2003, 2004 and 2005 and ten years of warming from 2003 to 2013.

Model	Model Terms	Effect Estimate	Std. Error	DF	t-value	P-value
2003	Ungrazed	1.52186	0.15467	22.28300	9.839	1.43e-09 ***
	1 hr grazed	-0.35378	0.18288	21.99500	-1.935	0.066
Grazing*Warming+1|block	5 hr grazed	-0.90996	0.18288	21.99500	-4.976	5.59e-05 ***
Block accounts for 5% of the variation.	OTC	0.07902	0.14932	21.99500	0.529	0.602
	Ungrazed	1.2109	0.1943	19.6650	6.232	4.71e-06 ***
2005	1 Hr grazed	-0.5336	0.2637	19.4350	-2.023	0.05705
Grazing*warming+1|block	5 Hr grazed	-0.1431	0.2472	19.0840	-0.579	0.56931
	OTC	-0.1321	0.2472	19.0840	-0.535	0.59910
Block account for 19% of the variation	1 hr grazed:otc	1.1617	0.3615	19.2720	3.214	0.00451 **
	5 hr grazed:otc	-0.2335	0.3496	19.0840	-0.668	0.51209
2013	Ungrazed	1.46825	0.17964	12.69400	8.173	2.07e-06 ***
Grazing*Warming+1|block	1 hr grazed	0.18414	0.17543	21.99400	1.050	0.30527
	5 hr grazed	0.01685	0.17543	21.99400	0.096	0.92435
Block accounts for 31% of the variation.	OTC	0.47467	0.14324	21.99400	3.314	0.00316 **

Table 12. Results from linear mixed models for the Graminoids in 2003, 2004 and 2005. Data is from the FRAGILE wet tundra site, summarizing the effects of grazing in the years 2003, 2004 and 2005 and ten years of warming from 2003 to 2013.

Model	Model Terms	Effect Estimate	Std. Error	DF	t-value	P-value
2003	Ungrazed	1.75611	0.09897	5.81200	17.745	2.77e-06 ***
	1 hr grazed	0.15208	0.05833	21.98300	2.607	0.0161 *
Grazing*Warming+1|block	5 hr grazed	0.04263	0.05833	21.98300	0.731	0.4726
Block accounts for 68% of the variation.	OTC	0.05837	0.04763	21.98300	1.226	0.2333
2005	Ungrazed	1.54378	0.09325	12.62900	16.555	6.14e-10 ***
Grazing*warming+1|block	1 Hr grazed	0.18874	0.09089	21.98900	2.077	0.0497 *
	5 Hr grazed	-0.10103	0.09089	21.98900	-1.112	0.2783
Block account for 31% of the variation	OTC	-0.01978	0.07421	21.98900	-0.266	0.7923
2013	Ungrazed	1.61258	0.12821	12.35400	12.578	2.09e-08 ***
Grazing*Warming+1|block	1 hr grazed	0.15126	0.12391	21.99200	1.221	0.235116
	5 hr grazed	0.04674	0.12391	21.99200	0.377	0.709647
Block accounts for 30% of the variation.	OTC	0.45061	0.10117	21.99200	4.454	0.000199 ***

Table 13. Results from linear mixed models for the Forbs in 2003, 2004 and 2005. Data is from the FRAGILE wet tundra site, summarizing the effects of grazing in the years 2003, 2004 and 2005 and ten years of warming from 2003 to 2013.

Model	Model Terms	Effect Estimate	Std. Error	DF	t-value	P-value
2003 Grazing*Warming+1|block Block accounts for 5% of the variation.	Ungrazed	0.82744	0.21063	9.35700	3.928	0.00321 **
	1 hr grazed	-0.01847	0.18708	17.14900	-0.099	0.92251
	5 hr grazed	-0.08765	0.19423	16.95400	-0.451	0.65753
	OTC	0.08207	0.18708	17.14900	0.439	0.66636
	1 hr grazed:OTC	-0.24037	0.25530	17.05900	-0.942	0.35958
	5 hr grazed:OTC	-0.17131	0.26967	17.04800	-0.635	0.53369
2005 Grazing*warming+1|block Block account for 19% of the variation	Ungrazed	0.60607	0.27394	10.54900	2.212	0.050
	1 Hr grazed	0.08913	0.26076	15.16600	0.342	0.737
	5 Hr grazed	-0.32518	0.29780	15.20000	-1.092	0.292
	OTC	0.19431	0.27900	15.34700	0.696	0.497
	1 hr grazed:otc	-0.33508	0.38160	15.24700	-0.878	0.394
	5 hr grazed:otc	0.03607	0.40075	15.32700	0.090	0.929
2013 Grazing*Warming+1|block Block accounts for 31% of the variation.	Ungrazed	0.85800	0.34360	6.99900	2.497	0.0412 *
	1 hr grazed	0.80476	0.59514	6.99900	1.352	0.2184
	5 hr grazed	0.09354	0.48593	6.99900	0.193	0.8528
	OTC	-0.04755	0.44359	6.99900	-0.107	0.9176
	1 hr grazed:OTC	-0.82734	0.71527	6.99900	6.99900	1.157
	5 hr grazed:OTC	-0.08227	0.65795	6.99900	-0.125	0.9040

Table 14. Results from linear mixed models for the Bryophytes in 2003, 2004 and 2005. Data is from the FRAGILE wet tundra site, summarizing the effects of grazing in the years 2003, 2004 and 2005 and ten years of warming from 2003 to 2013.

Model	Model Terms	Effect Estimate	Std. Error	DF	t-value	P-value
2003 Grazing+Warming+1|block Block accounts for 5% of the variation.	Ungrazed	2.015580	0.025674	10.964000	78.506	2.22e-16 ***
	1 hr grazed	-0.018015	0.023638	21.958000	-0.762	0.4541
	5 hr grazed	-0.003304	0.023638	21.958000	-0.140	0.8901
	OTC	0.041291	0.019300	21.958000	2.139	0.0438 *
2005 Grazing+warming+1|block Block account for 24% of the variation	Ungrazed	1.942457	0.028207	14.024000	68.864	< 2e-16 ***
	1 Hr grazed	-0.048019	0.028570	21.966000	-1.681	0.107
	5 Hr grazed	-0.150316	0.028570	21.966000	-5.261	2.82e-05 ***
	OTC	-0.001944	0.023327	21.966000	-0.083	0.934
2013 Grazing+Warming+1|block Block accounts for 34% of the variation.	Ungrazed	2.015580	0.025674	10.964000	78.506	2.22e-16 ***
	1 hr grazed	-0.018015	0.023638	21.958000	-0.762	0.4541
	5 hr grazed	-0.003304	0.023638	21.958000	-0.140	0.8901
	OTC	0.041291	0.019300	21.958000	2.139	0.0438 *