Norwegian University
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Effect of experimental warming on *Dryas octopetala*- dominated vegetation in High Arctic versus alpine ecosystems

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Natural Resource Management

Dryas octopetala in the High Arctic site, Endalen, June 2023.
Photo: Ida Christine Apalnes

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Preface

This study, completing my master's degree in nature resource management, has been long in the making, and application for a field grant started already in late 2022. Since then, it has been both challenging and incredibly rewarding, from application confusions and deadlines, through fieldwork in record-high temperatures on Svalbard and the extreme weather "Hans" on the mainland. Preliminary results from this thesis were presented at the Svalbard Science Conference in 2023, providing me with valuable experience in science outreach and networking. Through it all, my supervisors have given me valuable insight and guidance with my fieldwork, data analysis, and the creation of this thesis, and therefore, I give a big thanks to Siri Lie Olsen and Simone I. Lang. I would also like to show my gratitude to Forskningsrådet, for giving me the Arctic Field Grant and providing me with the means to conduct my fieldwork on Svalbard. In addition, thank you to Finse research station, for your hospitality during my stay.

Lastly, I would like to thank Merle Scheiner for cooperation in the field on Svalbard, and Gaute Eiterjord for field cooperation at Finse, as well as for sharing thoughts, ideas, and relevant papers throughout this process. Thank you, Fredrik Selmer, for laughs, snacks, and support while working together at various places in Longyearbyen and in Ås.

Abstract

As a consequence of climate change, colder regions such as the Arctic and alpine areas are experiencing a higher rate of warming compared to the global average. The effect of warming varies across the tundra biome, and the differences in vegetation composition and soil moisture further contribute to this variation. To monitor and better understand the effect of climate change on the tundra vegetation, the International Tundra Experiment (ITEX) uses open-top chambers (OTCs) located at different sites across the Arctic, which simulate anthropogenic climate change by increasing air and soil temperature. The dwarf shrub *Dryas octopetala* is one of few species with circumpolar distribution and can be found in both High Arctic and alpine regions, making it ideal for studying the effect of warming across sites. This thesis examined the effect of warming on *D. octopetala* at two different sites, one located in Endalen on the High Arctic Archipelago of Svalbard, and the other in the alpine site Finse, on the Norwegian mainland. The study aimed to assess how experimental warming affected the dwarf shrub in terms of abundance, plant height, and NDVI, and whether there was a correlation between these variables and soil moisture. Lastly, the study investigated the difference in species composition and richness after over 20 years of experimental warming.

The two sites displayed both different and similar responses to warming. Species richness and composition did not differ between control and OTC warming plots in either site. In the alpine site, the cover of bryophytes and lichens increased with higher soil moisture and with taller *D. octopetala*. There was a negative relationship between soil moisture and NDVI with warming in the alpine site, whereas in the High Arctic site, this relationship was positive. In both sites, higher cover of *D. octopetala* was positively correlated with NDVI. The results from this study suggest that *D. octopetala* experiences unfavourable conditions with increased warming in the alpine site, whereas in the colder High Arctic site, this "tipping point" has not yet been reached. The findings from this study highlight the importance of context dependency when investigating warming effects on the tundra vegetation.

Sammendrag

Temperaturøkningen som følge av klimaendringer er dobbelt så raskt i kalde miljøer slik som Arktis og alpine områder sammenlignet med det globale gjennomsnittet. Effekten av oppvarmingen varierer mellom ulike steder på tundraen, og variabler som vegetasjons sammensetning og jordfuktighet bidrar til denne variasjonen. For å overvåke og øke kunnskapen om hvordan klimaendringene påvirker vegetasjonen på tundraen bruker «The International Tundra Experiment» (ITEX) «open-top chambers». Disse er plassert på en rekke lokaliteter over hele Arktis for å simulere effekten av menneskeskapte klimaendringer ved å øke luft- og jordtemperaturen inni kammeret. Reinrose (*Dryas octopetala)* er en dvergbusk som vokser sirkumpolart og i alpine områder som gjør den ideell for å undersøke effekten av oppvarming på ulike lokasjoner. Denne studien undersøkte effekten av oppvarming på *D. octopetala* på en høyarktisk lokalitet i Endalen, Svalbard, og en alpin lokalitet, Finse, på fastlandet. Formålet med studien var å undersøke hvordan økte temperaturer påvirker *D. octopetala* i form av mengde, høyde, og NDVI, samt om det er var en korrelasjon mellom disse variablene og jordfuktighet. Til slutt undersøkte jeg om over 20 års oppvarming endret artssammensetningen på lokalitetene.

De to lokalitetene utviste både like og ulike responser til oppvarming. Hverken på den alpine eller den høyarktiske lokaliteten var det forskjell i artssammensetning ved høyere temperaturer. Dekningsgrad av mose og lav var høyere ved økt jordfuktighet og når *D. octopetala* var høyere. Videre var det et negativt forhold mellom jordfuktighet og NDVI med oppvarming på den alpine lokaliteten, mens det samme forholdet var positivt på den høyarktiske lokaliteten. På begge lokalitetene var det et positivt forhold mellom dekningsgrad av *D. octopetala* og NDVI. Resultatene fra denne studien indikerer at oppvarming fører til ugunstige forhold for *D. octopetala* ved den alpine lokaliteten, mens oppvarming på den høyarktiske lokaliteten ikke har ført til et slikt vippepunkt enda. Studien understreker viktigheten av lokale forhold og variasjoner på responsen tundra vegetasjonen utviser ved økte temperaturer.

Table of content

1. Introduction

The average global surface temperature has increased by 1.09°C over the last century, with the last 50 years being the fastest warming period in over two thousand years (IPCC, 2023). Ecosystems worldwide are affected by climate change (Walther et al., 2002), which threatens biodiversity by altering the structure and function of the systems (Verrall & Pickering, 2020). The effect of climate change on the ecosystems depends on the geographical location, and local conditions, as well as their vulnerability and ability to adapt to changes (Cowles et al., 2018). Ecosystems situated at higher altitudes and latitudes, such as in the Arctic and alpine regions, are experiencing a higher rate of warming than the global average (IPCC, 2018). Monitoring the biotic changes in these first responding environments is therefore vital for understanding the consequences of global climate change (Theurillat & Guisan, 2001; Walker et al., 2006)

Warmer temperatures in the tundra biome are linked to increased height and cover of graminoids and deciduous shrubs (Elmendorf et al., 2012a; Walker et al., 2006). The latter is often referred to as "shrubification" (Mekonnen et al., 2021) and contributes to an enhancement of plant productivity and biomass, the so-called "Arctic greening" (Phoenix & Treharne, 2022). A way to monitor and quantify greening is by using the satellite-based normalized difference vegetation index (NDVI), which has been shown to strongly correlate with the vegetations photosynthetic activity (Anyamba & Tucker, 2005; Myneni et al., 1995). NDVI has been increasing over the last two decades (Jia et al., 2009), and such trends can be used as a proxy for greening. Simultaneously with shrubification, the cover of bryophytes and lichens, as well as the area of bare ground, decreases with warming (Elmendorf et al., 2012b). The extent of the vegetation changes depends on the degree and duration of warming, highlighting the importance of long-term monitoring (Elmendorf et al., 2012a; Elmendorf et al., 2012b; Mekonnen et al., 2021; Oberbauer et al., 2013; Walker et al., 2006).

Arctic greening is expected to create a positive feedback loop, where the increased plant biomass can directly decrease surface albedo due to taller and darker canopies, leading to higher absorption of sunrays and thus, increased warming (Chapin III et al., 2005; Euskirchen et al., 2009; Pearson et al., 2013). Further, shrubs trap and hold snow, subsequently increasing the snow depth which in turn leads to a higher soil temperature during winter (Sturm et al., 2005). The increase in soil temperature promotes a higher microbial activity, contributing to more plant-available nitrogen. During the growing season, this available nitrogen favours shrub growth, thus reinforcing greening and the dominance of shrubs (Sturm et al., 2005). Consequently, Arctic and subarctic species experience a shift in species composition and

abundance due to rises in temperatures, with woody plants benefiting the most (Danby & Hik, 2007; Harsch et al., 2009), resulting in an overall reduction in species diversity and evenness of the vegetation (Walker et al., 2006).

Warming–induced changes that occur within the tundra ecosystem are uneven across the biome, and plant communities are more responsive to change at warmer, low Arctic sites than in colder, High Arctic areas (Elmendorf et al., 2012a; Elmendorf et al., 2012b). In Elmendorf et al. (2012a) the effect of warming on the abundance of shrubs was higher in sites that were warmer to begin with, whereas graminoids increased most in colder sites. Additionally, soil moisture has been shown to be an important moderator for the effect of warming on vegetation, and Elmendorf et al. (2012a) found that the response to warming of deciduous shrubs was stronger in wet sites than in drier. This interaction between soil moisture and ambient temperature is suggested as a possible explanation as to why the decrease of bryophytes and lichens with rising temperature is uneven across the tundra (Cornelissen et al., 2001; Lang et al., 2012). Thus, the vegetation response to climate warming may differ depending on where the tundra is geographically located, and understanding the factors contributing to these differences is important when predicting the effect of climate change on the tundra ecosystem.

To monitor and better understand the effects of climate change on tundra vegetation, the International Tundra Experiment (ITEX) was founded in 1990 (Molau & Mølgaard, 1996). The experiment has sites throughout the Arctic, allowing for examination of the vegetation across the tundra biome. The ITEX network uses a passive warming design with open-top chambers (hereafter OTC), which are used to elevate both the air and soil temperature. This is done to simulate anthropogenic climate change while maintaining the vegetation and allowing natural processes to unfold (Molau & Mølgaard, 1996). Through the ITEX network, several multi-site studies have been conducted, documenting the effect of warming on the vegetation and illustrating the importance of local factors contributing to vegetation response (Chapin III et al., 1995; Elmendorf et al., 2012a; Elmendorf et al., 2012b; Hollister et al., 2005).

The dwarf shrub *Dryas octopetala* is one of few species that has both circumpolar distributions as well as being present in alpine habitats (Komárková & Webber, 1978; Mcgraw, 1985; Rønning, 1969), making it ideal for studying the effect of warming across-sites at different altitude and latitudes. *D. octopetala* is considered a "winter green" species, due to the same leaves being photosynthetic for several years, although the chlorophyll degrades during winter (Elkington, 1971; Rønning, 1969; Welker et al., 1997). The species grows in mats on the tundra and is typically found in areas that have thin snow cover during winter. Furthermore, it is an

indicator species for biological hotspots with high species richness (Klanderud & Totland, 2005). *D. octopetala* is classified as near threatened (NT) on the Norwegian mainland due to the continued habitat degradation following rising temperatures (Solstad et al., 2021a). On Svalbard however, the species is considered to be of least concern (LC), and it is believed that the population, as well as its distribution, will increase in the future (Solstad et al., 2021b).

In this study, I examined two ITEX sites, one located on the High Arctic Archipelago of Svalbard, and the other situated in the alpine region of the Norwegian mainland. The focus of this study is on the difference in responses to warming of *D. octopetala*, such as plant height and photosynthesis, measured as NDVI, and abundance, between the High Arctic and the alpine site. In addition, the study investigates the effect of warming on plant species richness and composition. Lastly, I wish to investigate whether there is a correlation between the aforementioned biotic variables and soil moisture.

The main hypotheses are:

(i)   Species richness will decrease, and species composition will change with warming in both sites.

(ii)   Abundance of *Dryas octopetala* will increase with warming in both sites.

(iii)   Plant height of *Dryas octopetala* will be higher in the alpine site than in the High Arctic site and will be more prominent with warming.

(iv)   Increase in height and greening will be more pronounced in areas with higher soil moisture and will be higher in the alpine site than in the High Arctic site.

2. Materials and methods

2.1 Study area

2.1.1 Endalen, High Arctic

Svalbard is an archipelago in the High Arctic between 74-81°N and 10-30°E. The study site is situated on a south-facing slope in Endalen (78.18°N, 15.75°E), approximately four kilometres from Longyearbyen (Figure 1). The mean temperature for the growing season, (June, July, August) between 2003 and - 2023 was 6.1°C, measured at Svalbard Airport, the nearest weather station (Norwegian Meteorological Institute, 2024). The bedrock in the site consists of various sedimentary rocks and gives rise to a calcareous soil (Aarrestad et al., 2010). The ITEX warming experiment in Endalen was established in 2001 and three characteristic High Arctic communities, a snowbed, a *Cassiope* heath and a *Dryas* heath, were selected based on differences in growing season and snowmelt (Jonsdottir et al., 2023). My fieldwork related to this master thesis was focused on the drier *Dryas octopetala* heath, with relatively thin snow cover (ca. 10 cm) and early snowmelt.

Figure 1: Location of the High Arctic study site in Endalen, on the biggest island, Spitsbergen, on the High Arctic Archipelago Svalbard. Map from ©topoSvalbard.npolar.no, (TopoSvalbard, 2024).

2.1.2 Finse, alpine

The study site is situated on a southwest-facing ridge on the mountain Sanddalsnuten (60.626°N, 7.522°E), 1554 meters above sea level. Sanddalsnuten is located in the northern part of Hardangervidda mountain plateau in Finse, Ulvik municipality in southwest Norway (Figure

2). The ITEX experiment was established on the site in 2000. The mean temperature during June, July, and August between 2003-2023 was 8.4°C, measured at Finsevatn (Norwegian Meteorological Institute, 2024). The study site is exposed to high wind speed, leading to low accumulation of snow during winter (Klanderud & Totland, 2004). The main plant community consist of a species-rich heath dominated by *D. octopetala*, supported by a phyllite-dominated bedrock (Olsen & Klanderud, 2014).
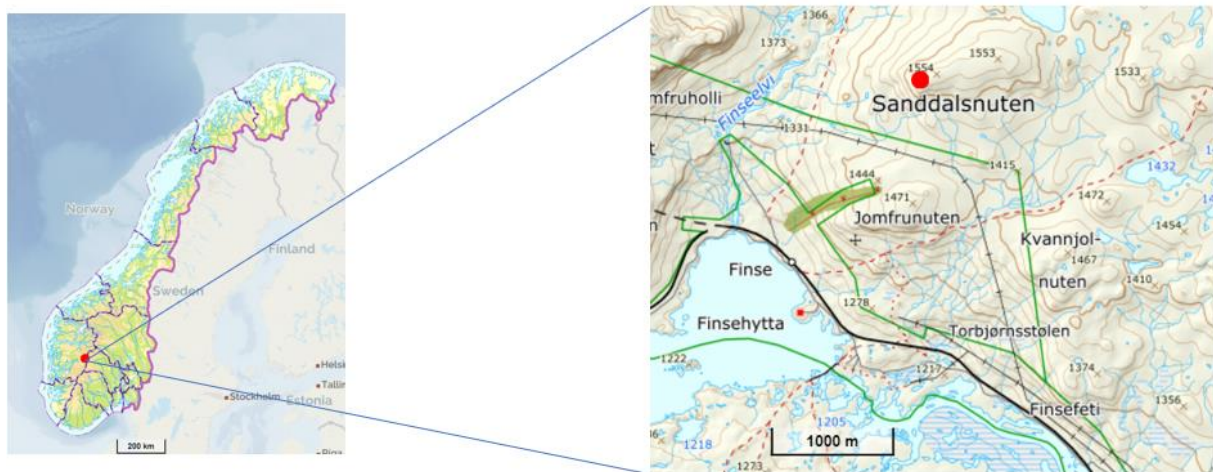

Figure 2: Location of the alpine site at Finse, mainland Norway. Map from ©norgeskart.no, (Kartverket, 2024).

2.2 Data sampling

Open-top chambers (OTC) are used in both sites to simulate warming linked to climate change. The chambers consist of six walls made from plexiglass with an opening at the top (Figure 3). This design ensures exchange of water and CO_2, while simultaneously allowing light, pollinators, and herbivores access to the plot (Molau & Mølgaard, 1996). OTC increases the air temperature within the chamber by approximately 1.5°C and the soil temperature by 1°C (Olsen & Klanderud, 2014; Vandvik et al., 2023), while minimizing the effect of wind on the vegetation (Hollister et al., 2022). Further analysis of OTC performance and potential unintentional effects on the vegetation can be found in Hollister et al. (2022) and Marion (1996).

In total, ten plots dominated by *D. octopetala* were selected at each site, five warmed and five controls. In the High Arctic site, the ten *D. octopetala* plots were the only plots at the site and dominated by this species. The alpine site is considered a *D. octopetala* heath, and all plots dominated by *D. octopetala* were selected and given a number. Out of these plots, ten were randomly selected using a number generator.

Figure 3: OTC warming plots on the south-facing ridge of Sanddalsnuten at the alpine site, August 2023. Photo: Ida Christine Apalnes.

2.2.1 Vegetation analysis

As a safety measure, all fieldwork was conducted by a minimum of two people at both sites. The analysis was carried out using the site-specific protocol for each location.

The vegetation analysis in the High Arctic site was conducted in the summer of 2022 using a point frame method. The point frame was 75 × 75cm divided into 10 × 10 subplots using two sets of strings, which created an overlapping grid within the frame (Figure 4a). The frame was placed horizontally over the plot and neither the frame nor the grid was to touch the vegetation. Before starting the analysis, I aligned the two sets of strings by standing over the plot while "aiming" with one eye closed. Once the two grids were seen as one, I could start the recording by inserting a measuring stick through the right corner of each 10 × 10 subplot. If the same species were hit several times, it was counted as individual hits, whereas "litter" was only counted once. During the summer of 2023, cover % of *D. octopetala* as well as bryophytes and lichens were visually estimated in the High Arctic site.

The vegetation recording in the alpine site was conducted summer of 2023 using subplot frequency (Figure 4b). The plots were 60 × 60cm, divided into two split-plots (30 × 60cm) which were further divided into 18 equal subplots (10 × 10cm) (Figure 4b). In each sub-plot, the presence of lichens, bryophytes and vascular plant species was noted, and the cover (%) was visually estimated for each split-plot. The split-plot measurements were combined to create a mean for the entire plot.

Figure 4: **a)** The point intercept frame used when conducting vegetation analysis in the High Arctic site. The red spot represents where the recording started. The frame was divided into 10×10 squares, from A1 to J10. Photo: Merle Scheiner. **b)** The frame used for vegetation analysis in the alpine site. The frame was 30×60 cm and used for recording one sub-plot at a time. Photo: Gaute Eiterjord.

2.2.2 *D. octopetala* height

Plant height of *D. octopetala* was measured four times within each plot in the High Arctic site and six times in the alpine site. As old, dead leaves of *D. octopetala* are still attached to the plant as it grows, the measuring tool was not forced into the ground or litter. In the High Arctic site, four aluminium "balls" were thrown into the plot and the height of the closest *D. octopetala* was measured. In the alpine location, the height of *D. octopetala* was measured in the same subplot (nr. 1, 9 and 18) for each split-plot. If there was no *D. octopetala* present within a subplot, the nearest subplot containing the species was used. The mean height was calculated for each plot.

2.2.3 NDVI

NDVI was measured once per month during the growing season, June, July, and August. If feasible, I attempted to measure approximately the same time each month, coordinating between the two sites. The NDVI measurements in the High Arctic site were collected using Skye's SpectorSense 2+ (Sky Instruments Ltd, United Kingdom). The device was mounted on a 90 cm pole. Three measurements were taken in the High Arctic site, one from the bottom, left and right side of the plot, facing upslope, and the means were calculated for each month. In the

alpine site, only one measurement was taken for each subplot using a Greenseeker (Trimble Inc., USA). The mean seasonal NDVI per plot was calculated by averaging all monthly measurements taken throughout the season.

2.2.4 Soil moisture

Soil moisture was measured the same day, or one day after the NDVI measurement in both locations. In the alpine site a Delta- T SM150 (Delta-T Devices Ltd., England) was used, whereas in the High Arctic site, I used a Delta-T ML3 (Delta-T Devices Ltd., England). Both soil moisture meters used the mineral soil setting. The instruments were gently pushed all the way into the soil so that the measuring rods were fully covered. In the High Arctic site, three measurements were taken per plot, two by the top corners, and one by the bottom right corner, facing upslope. In order to not disturb the vegetation, the measurement was taken slightly outside the plot in the High Arctic site. In the alpine site, soil moisture was measured once in each corner within the plot. In both locations, it was difficult to get a reading in several plots due to limited amount of soil and a high number of rocks, and in such cases, the measurements were taken as close as possible to the plot. The seasonal mean was calculated from the monthly means for each plot. Due to logistical constraints, the last measurement in the alpine site was approximately on the 13th of August, while in the High Arctic site, the August measurement was conducted towards the end of the month.

2.3 Statistical analysis

Statistical analyses were conducted using the software R version 4.3.2 (R Core Team, 2022) and R studio (Build 402) (Posit team, 2024). The data collected on cover %, soil moisture and NDVI exhibited a non-normal distribution, and log transformation, square root and cube root transformation were tried in order to achieve normal distribution, with limited success. Thus, non-parametric tests were used (see below).

Shannon diversity index (H) and Simpson diversity index (D) were calculated in R using the "vegan" package (Oksanen et al., 2022) to examine the effect of warming on species diversity in the two sites. When calculating these indexes, presence/absence data of the species recorded during vegetation analysis were used. The Shannon diversity index is defined as $H = -\Sigma\, p_i$ $\ln(p_i)$, where p_i is the relative abundance of species i (Shannon, 1948). The Simpson diversity index is defined as $D = 1 - \left(\frac{\Sigma n(n-1)}{N-(N-1)}\right)$, where n is the total number of a particular species, and N is the total number of all species (Simpson, 1949). Thus, the Shannon diversity index is

more sensitive to rare species, whereas the Simpson diversity index gives more weight to dominant species (Nagendra, 2002).

To investigate whether there was a change in the vegetation after over 20 years of warming, control versus OTC warming plots were tested against cover, and height of *D. octopetala,* soil moisture, NDVI, total number of species, cover of bryophytes and lichens, and the two diversity indexes, using a Mann- Whitney U tests. Further, Spearman correlation tests were conducted to test whether the cover and height of *D. octopetala* and NDVI were related to soil moisture. In addition, I examined whether NDVI, soil moisture, cover, and height of *D. octopetala* had any significant relationships to the total number of species recorded. For the Spearman correlation tests, the data was split into two different datasets where control plots and OTC warming plots were separated. This was done to examine if the relationships were different between the two treatments.

In addition, I wanted to investigate possible changes in species composition with warming. For this, a non-metric multidimensional scaling (NMDS) was conducted separately for each site, using the metaMDS function within the "vegan" R-package (Oksanen et al., 2022). The NMDS was run with two dimensions and Bray-Curti's dissimilarity measure for distance. The species data for this analysis were presence/absence within each plot. The species data from the alpine site contained bryophytes and lichens species, whereas this was not recorded in the High Arctic site. However, I chose to include the bryophytes and lichens species from the alpine site, despite not having similar data from the High Arctic site, to examine the effect of warming on the entire vegetation with all available data. Cover and height of *D. octopetala*, soil moisture, NDVI and cover of bryophytes and lichens were plotted in R-studio using the "envfit"-function within the "vegan" package (Oksanen et al., 2022). Further, the relationship between environmental variables and the NMDS- axes were examined to see whether they correlated with the species composition. In addition, a detrended correspondence analysis (DCA) was conducted and compared to the NMDS-axes with Kendall's rank correlation coefficient. To investigate if there was a difference in species composition with warming, a redundancy analysis (RDA), was conducted. RDA was chosen instead of a canonical correspondence analysis (CCA) since the length of DCA1 axis was less than 3 at both sites (Lepš & Šmilauer, 2003).

3. Results

3.1 Species richness and cover

The Mann- Whitney U test showed no significant effect of the warming treatment on the total number of species recorded in either site (Table 1, Figure 5). However, Figure 5 suggests a trend where the number of species is higher within control plots compared to OTC warming plots. In addition, the Mann- Whitney U test showed a significant difference with warming treatment on the cover of bryophytes and lichens in the alpine site, but not in the High Arctic site (Table 1, Figure 6). Further, the cover of bryophytes and lichens was significantly positively correlated with soil moisture within the OTC warming plots in the alpine site (Table 2). The Spearman rank correlation showed a significant positive relationship between *D. octopetala* height and the total number of species within control plots in the alpine site (Figure 7, Table 2). I found no significant effect of the warming treatment on either the Shannon (*H*) or the Simpson (*D*) diversity index, although there was a non-significant tendency for higher *D* values in the control plots in the alpine site (Table 1, Appendix 12).

Table 1: Results from the Mann- Whitney U test showing the difference in the cover of *D. octopetala* (Dryas) and bryophytes ("bryo") and lichens, soil moisture, NDVI, number of species per plot and Shannon and Simpson diversity index between control and OTC warming plots, for the alpine and the High Arctic site. n= 5 for both plot types on each location. Bold p-values are <0.05.

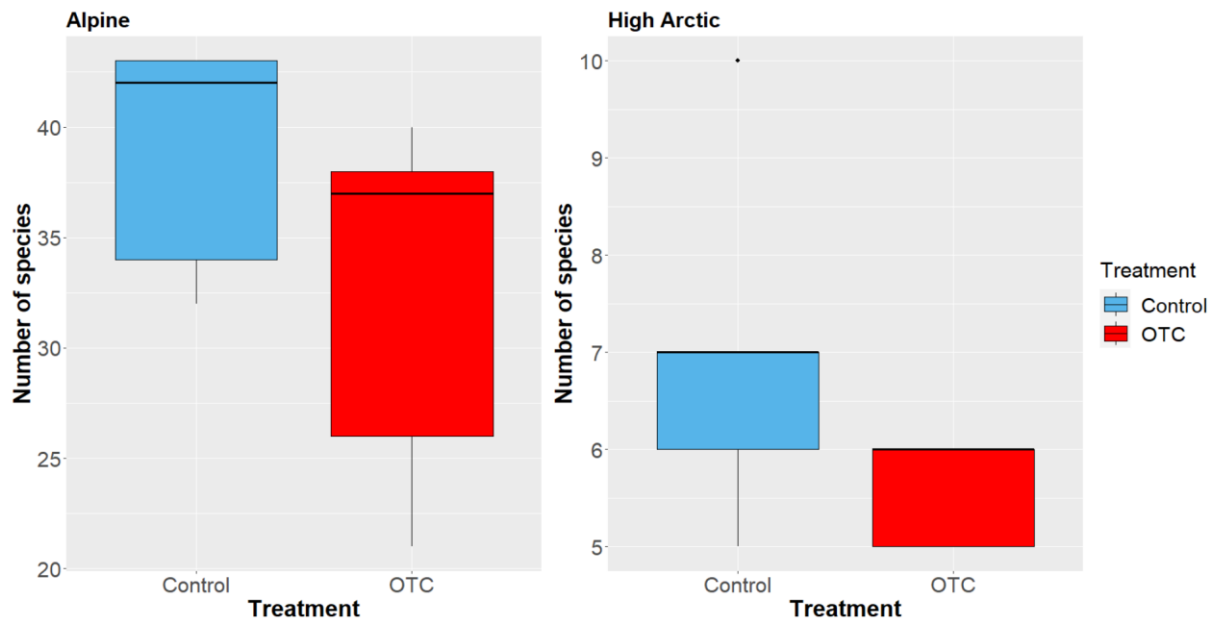| Variable	Alpine		High Arctic	
	W	**p-value**	**W**	**p-value**
Cover of Dryas	13.5	0.918	7	0.289
Height of Dryas	7	0.296	10	0.676
Moisture	22	0.060	20	0.144
NDVI	12	1	9	0.531
Number of species	19	0.209	19.5	0.154
Cover of bryo and lichen	25	**0.012**	12	1
Shannon diversity index	18	0.295	13	1
Simpson diversity index	21	0.095	17	0.381

Figure 5: The total number of species present within the control (blue) and OTC warming plots (red) in the alpine site (left) and the High Arctic site (right). n=5 for both plot types. Note the different scaling on the y-axis.
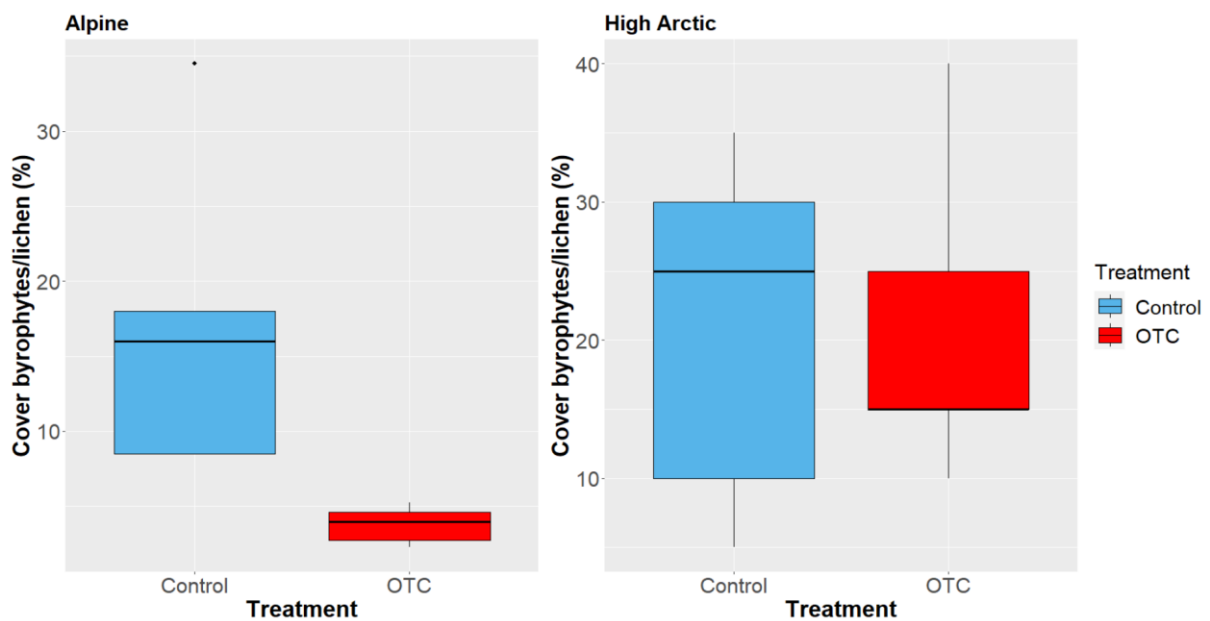

Figure 6: Cover of bryophytes and lichens (%) within the control (blue), and OTC warming plots (red) in the alpine site (left) and the High Arctic site (right). n= 5 for each plot type. Warming had a significant effect on the cover of bryophytes and lichens at the alpine site. Note the different scaling on the y-axis.
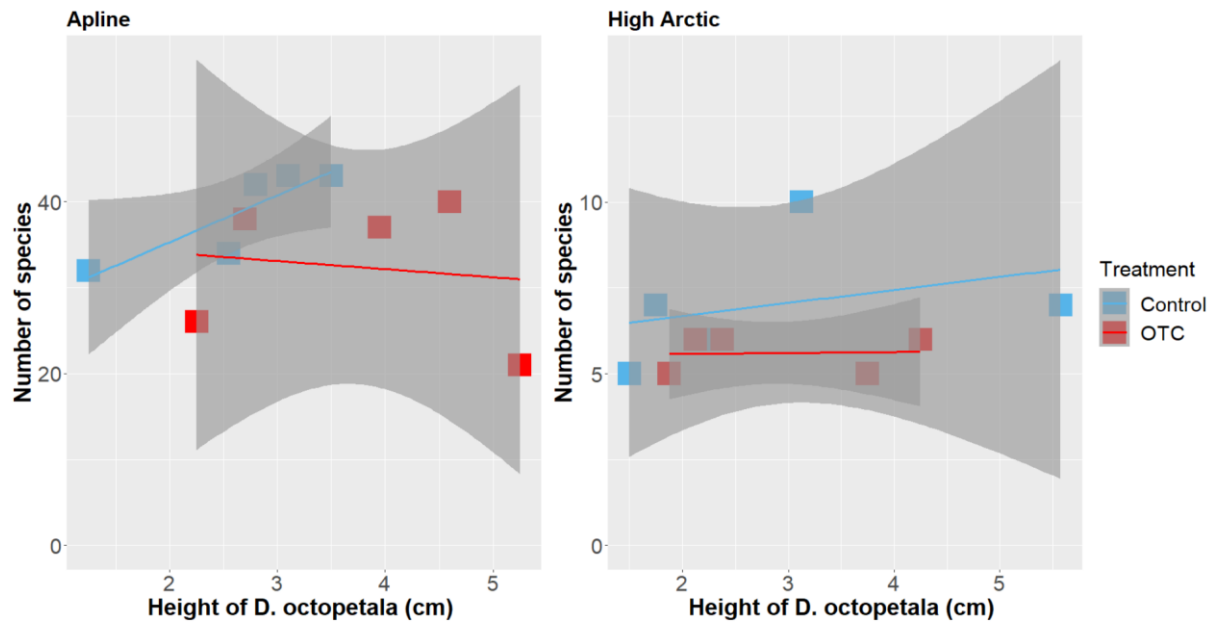
Figure 7: The total number of species plotted against the height of *D. octopetala* within control (blue) and OTC warming plots (red) in the alpine site (left) and the High Arctic site (right). n=5 for both plot types. In the alpine site, there was a significant positive relationship between the height of *D. octopetala* and total number of species within the control plots, whereas no statistical significance was found on the High Arctic site. The grey area shows 95% confidence intervals. Note the different scaling on the y-axis.

Table 2: The Spearman rank correlation (ρ) and associated p-value for the relationship between soil moisture and cover and height of *D. octopetala* ("Dryas"), NDVI, and cover of bryophytes ("bryo) and lichen, and the relationship between NDVI, soil moisture, cover, and height of *D. octopetala* and total number of species recorded, within the control plots and the OTC warming plots at the alpine site and the High Arctic site. n = 5 for both plot types. Bold p-values are <0.05.

| Predictor variable (x) | Response variable (y) | Alpine | | | | High Arctic | | | |
| | | Control | | OTC | | Control | | OTC | |
		p-value	ρ(rho)	p-value	ρ(rho)	p-value	ρ (rho)	p-value	ρ (rho)
Moisture	Cover of Dryas	0.683	-0.3	**0.005**	-0.974	0.553	-0.359	**0.041**	0.894
Moisture	Height of Dryas	0.517	0.4	0.95	-0.1	0.683	0.3	0.35	0.6
Moisture	NDVI	0.683	-0.3	0.083	-0.9	0.45	-0.5	**0.017**	1
Moisture	Cover of bryo and lichen	**0.054**	0.872	0.95	-0.1	1	0	0.322	0.564
NDVI	Number of species	0.805	-0.154	0.35	-0.6	0.74	-0.2	0.638	-0.289
NDVI	Height of Dryas	0.95	-0.1	0.683	0.3	0.233	-0.7	0.35	0.6
Cover of Dryas	NDVI	**0.017**	1	0.089	0.821	0.493	0.410	**0.041**	0.894
Moisture	Number of species	0.553	0.359	0.233	0.7	0.434	-0.462	0.638	-0.289
Cover of Dryas	Number of species	0.803	-0.154	0.269	-0.615	0.362	-0.526	0.239	-0.645
Height of Dryas	Number of species	**0.005**	0.974	0.95	-0.1	0.219	0.667	0.638	0.289

3.2 Species composition

There was no significant difference in species composition between the control and OTC warming plots in either site (Table 3, Figure 8, 9). See Appendix 13 for species plots.

Table 3: Results from the redundance analysis (RDA), testing whether the species composition was affected by the warming treatment in the alpine site and the High Arctic site. Presence/absence data of the species were used for the analysis.

	Df	Variance	F	p-value
Alpine	1	1.5111	1.2593	0.135
High Arctic	1	0.2556	1.4375	0.239

In the alpine site, I found that two environmental variables were significantly correlated with the NMDS-axes (Table 4). The cover of bryophytes and lichens, as well as the cover of *D. octopetala,* were positively correlated with NMDA axis 2 and 1, respectively. I did not find any correlation between the axes and any of the variables in the High Arctic site.

Table 4: Correlation between environmental variables and the two axes in non-multidimensional scaling (NMDS) made with presence/absence of species in the alpine and High Arctic site and soil moisture, cover of bryophytes ("bryo") and lichens, height, and cover of *D. octopetala* ("Dryas") and NDVI. Kendall's rank coefficient τ was used to measure correlations. Bold p-values are <0.05.

|		Alpine		High Arctic	
Variable	Axis	τ	p-value	τ	p-value
Moisture	NMDS1	-0.289	0.291	-0.067	0.862
	NMDS2	0.333	0.216	-0.156	0.601
Cover of bryo and lichen	NMDS1	-0.135	0.59	-0.184	0.449
	NMDS2	0.629	**0.012**	0.184	0.469
Height of Dryas	NMDS1	-0.244	0.381	-0.378	0.156
	NMDS2	0.289	0.291	0.156	0.601
Cover of Dryas	NMDS1	0.659	**0.009**	0.070	0.785
	NMDS2	0.159	0.528	-0.164	0.523
NDVI	NMDS1	0.378	0.156	-0.022	1
	NMDS2	0.2	0.484	-0.111	0.727
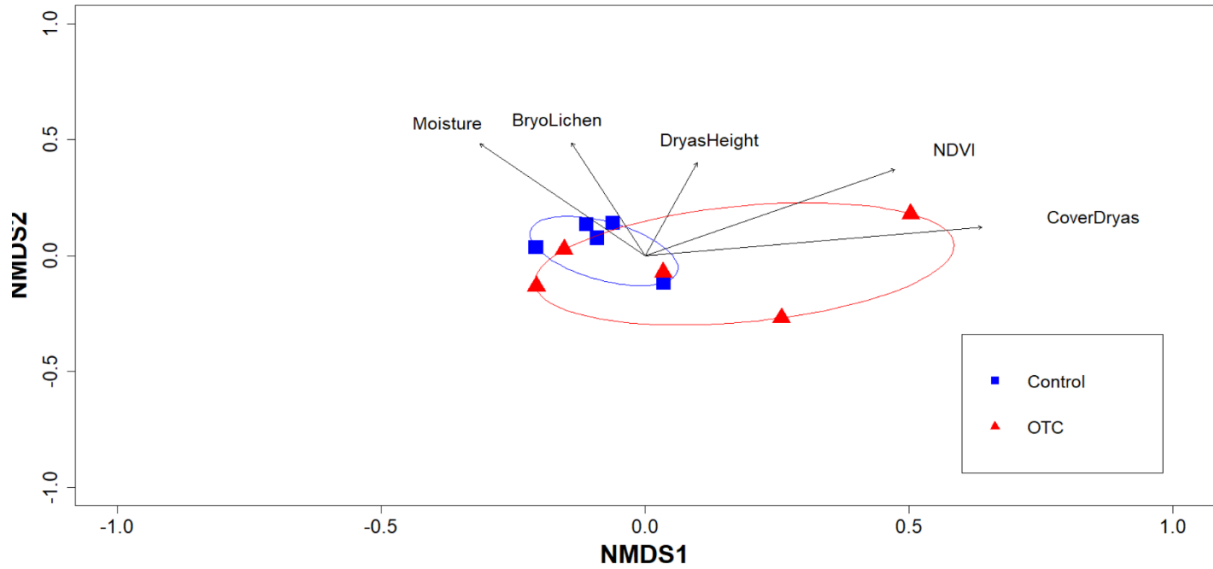
Figure 8: Nonmetric multidimensional scaling ordination for the two treatments in the alpine site with 95% confidence interval for control plots (blue) and OTC warming plots (red) along the two main NMDS-axis. The arrows indicate the correlation between the ordination and soil moisture, cover of bryophytes and lichens, cover and height of *D. octopetala* and NDVI. The length of the environmental vectors was scaled differently at the two sites to ensure that the vectors did not go beyond the plot boundaries. The length of the arrows is proportional to the strength of the correlation.
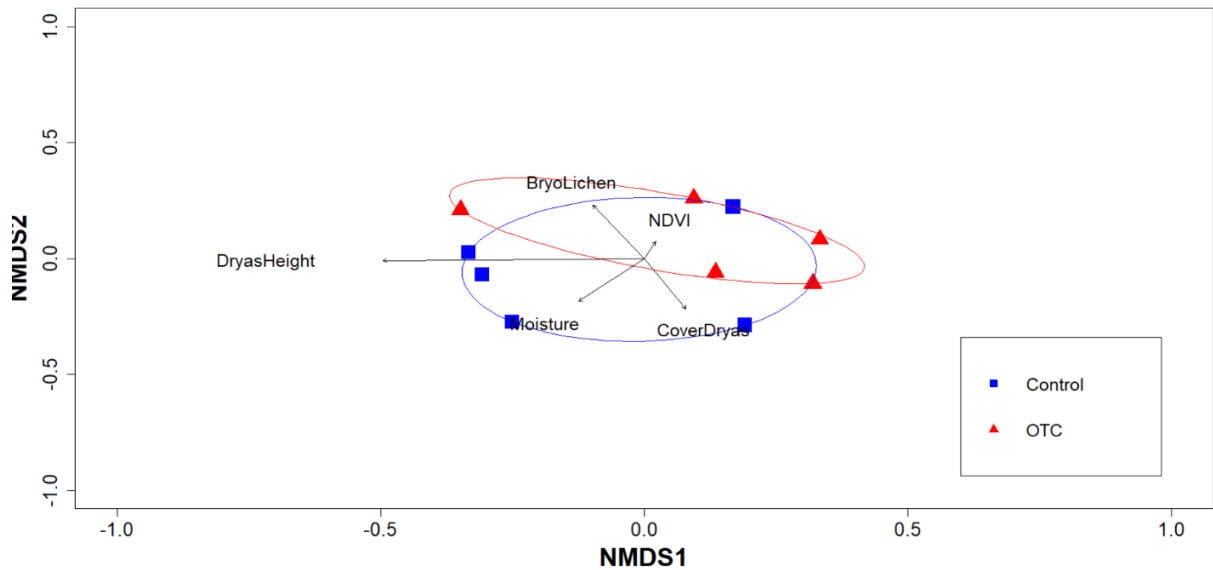

Figure 9: Nonmetric multidimensional scaling ordination for the two treatments at the High Arctic site with 95% confidence interval for control plots (blue) and OTC warming plots (red) along the two main NMDS-axis. The arrows indicate the correlation between the ordination and the soil moisture, cover of bryophytes and lichens, cover and height of *D. octopetala* and NDVI. The length of the environmental vectors was scaled differently at the two sites to ensure that the vectors did not go beyond the plot boundaries. The length of the arrows is proportional to the strength of the correlation.

3.3 Height, greening, moisture, and cover of *D. octopetala*

There was no significant difference in terms of height or cover of *D. octopetala* between the control plots and the OTC warming plots (Table 1, Appendix 14), or any relationship between the height of *D. octopetala* and soil moisture (Appendix 15) in either site. However, the Spearman rank correlation showed a significant relationship between the cover of *D. octopetala* and soil moisture within the OTC plot in both sites (Table 2, Figure 10), although the relationship was negative in the alpine site, but positive in the High Arctic site. Furthermore, within the OTC in the High Arctic site, NDVI had a significantly positive correlation with soil moisture (Table 2, Figure 10). In the alpine site, there was a tendency for higher soil moisture within control plots, although not significant (Table 1, Figure 11). In addition, the Spearman rank correlation showed that there was a tendency for a negative relationship between NDVI and soil moisture within the OTC plots in the alpine site, but this was not statistically significant (Table 2, Figure 10). There was a significant positive relationship between NDVI and cover of *D. octopetala* within control plots and a non-significant positive trend within the OTC warming plots in the alpine site. In the High Arctic site, the same significant positive relationship was observed in the OTC warming plots (Table 2, Appendix 16).
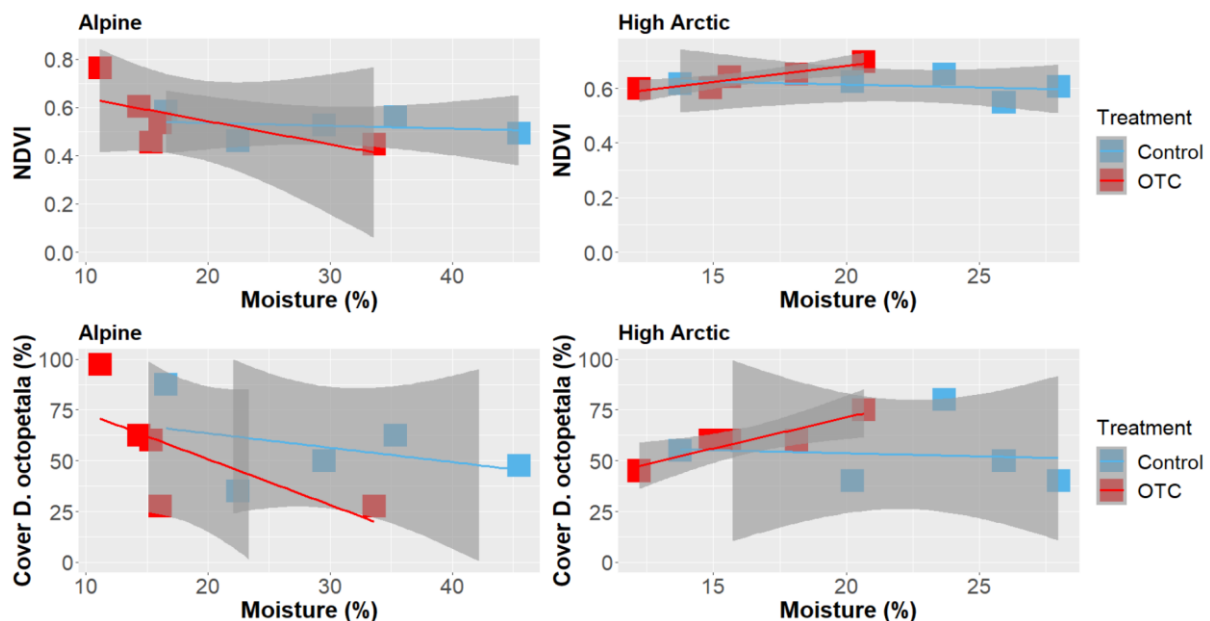

Figure 10: NDVI (above) and cover of *D. octopetala* (below) plotted against soil moisture within control (blue) and OTC warming plots (red) in the alpine location (left) and the High Arctic location (right). Grey area shows 95% confidential intervals. **Above**: There was a significant positive correlation between soil moisture and NDVI within the OTC plots in the High Arctic site. In the alpine site, there was a tendency for a negative relation between soil moisture and NDVI, although not significant. **Below**: There was a significant negative relationship between soil moisture and the cover of *D. octopetala* within

the OTC plots in the alpine site and a significant positive relationship within the OTC plots in the High Arctic site. Note the different scaling on the y-axis.
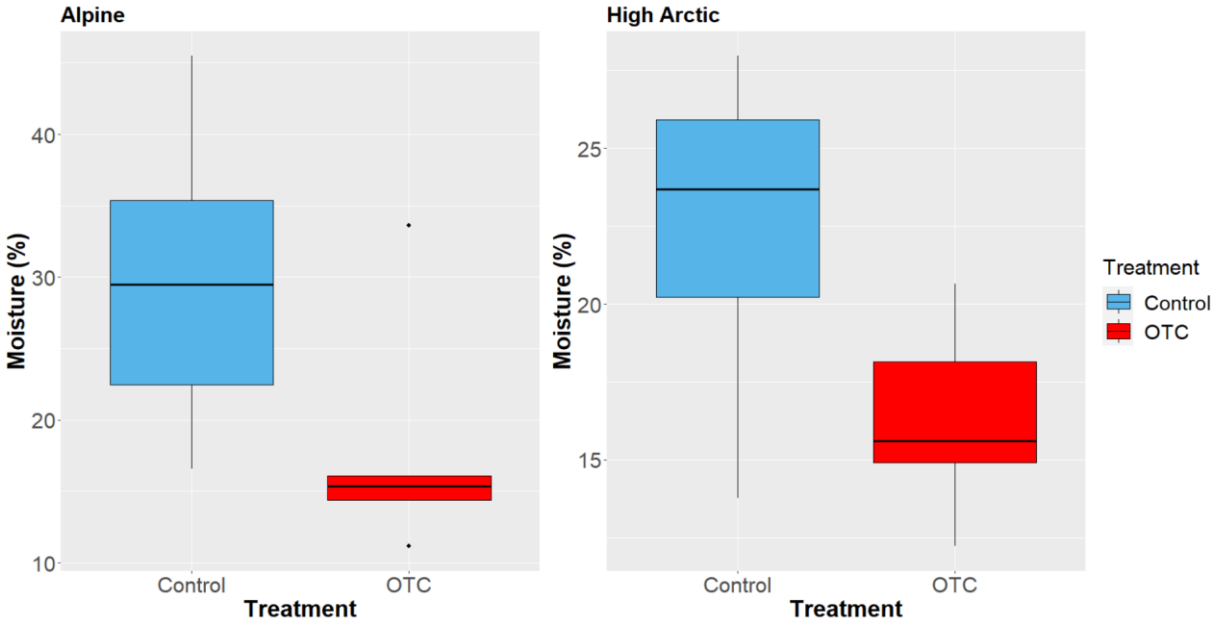

Figure 11: The effect of treatment on the soil moisture within control (blue), and OTC warming plots (red) in the alpine site (left) and the High Arctic site (right). n=5 for both treatments. In the alpine site, there was a non-significant difference between control and the warming treatment on the soil moisture. Note the different scaling on the y-axis.

4. Discussion

This study examined the effect of warming on the dwarf shrub *D. octopetala* in a High Arctic site and an alpine site with respect to abundance, plant height and NDVI, and whether there was a correlation between these variables and soil moisture. In addition, the study examined the effect of warming on the species richness and composition at the different sites.

Species richness and composition did not differ between control plot and OTC warming plots at either site. Soil moisture and *D. octopetala* height were positively related with cover of bryophytes and lichens in control plots in the alpine site, and soil moisture was strongly positively related with NDVI in OTC warming plots in the High Arctic site. However, in the alpine site, the relationship between soil moisture and NDVI exhibits a negative trend in the OTC warming plots. Increased cover of *D. octopetala* was positively correlated with NDVI in the control plots in the alpine site, and within the OTC warming plots in the High Arctic site. There was no significant relationship between soil moisture and height of *D. octopetala* at either site.

4.1 Changes in cover, height and greening of *D. octopetala* with warming

Cover of *D. octopetala* decreased with higher soil moisture within the OTC warming plots in the alpine site, whereas in the High Arctic site, the relationship was opposite. The findings in the alpine site are surprising and weaken my hypothesis that the abundance of *D. octopetala* would increase with soil moisture in both sites. Warming on moist soil has been shown to have a strong positive effect on the total abundance of shrubs, of which deciduous shrubs showed the highest increase (Elmendorf et al., 2012a). This expansion can further be facilitated as the availability of nitrogen is elevated when temperatures get warmer (Chapin III et al., 1995), and Manninen et al. (2024) found that N-fertilization increased the share of deciduous dwarf shrubs and graminoids at the expense of evergreen dwarf shrubs. Similarly, Klanderud & Totland (2005) found that the dominant *D. octopetala* was replaced by graminoids and forbs when warming was combined with fertilization. It is possible that *D. octopetala* is facing competition from species that can better utilise increased soil moisture, and potential nutrient availability, in addition to light limitation from increased litter. An increase in deciduous shrubs leads to a higher accumulation of litter (Elmendorf et al., 2012a), which can both limit light availability (Sorensen & Michelsen, 2011) and physically smother the underlying vegetation (Gough et al., 2016). Indeed, Eiterjord (2024) found significantly more litter and a higher cover of dead *D. octopetala* with warming in the alpine site, and especially during the 2018 heat wave, excessive

wittering and drying of the *D. octopetala* cover was observed (S. Lie Olsen, personal communication, April 2024). Further, NDVI showed a negative relationship with soil moisture within the OTC warming plots in the alpine site, indicating that either more species are declining, or that the amount of dead material has indeed increased, leading to a browner surface and thus, lower NDVI values. On the other hand, there was a strong, positive relationship between NDVI and the cover of *D. octopetala* within control plots at the alpine site. Thus, it is possible that warming in the alpine site has exceeded an initial, positive effect on *D. octopetala*, and instead has reached a tipping point where the conditions within the OTC warming plots are becoming unfavourable by potentially exceeding maximum temperature for optimal growth (Elmendorf & Hollister, 2023; Marchand et al., 2005).

In the High Arctic site, both cover of *D. octopetala* and NDVI increased with soil moisture within the OTC warming plots. The temperature in the High Arctic site is lower compared to the alpine site (Norwegian Meteorological Institute, 2024), suggesting that potential temperature stress is unlikely. However, the mean temperature recorded at the Svalbard airport in June 2023, was 10.1°C, which is the highest monthly mean temperature documented since the recordings started in 1975 (Norwegian Meteorological Institute, 2024). Elmendorf & Hollister (2023) found a lack of phenological responses to warming above 10°C in Arctic plant communities, suggesting that the vegetation would not benefit from increased temperatures beyond that point and that the vegetation might experience heat stress at relatively low temperatures. This indicates that the High Arctic could experience a decrease in *D. octopetala* cover similar to the alpine site with increasing temperatures in the future. The estimated cover of dead *D. octopetala* and litter were not recorded in the High Arctic site, but future studies should include these measurements to monitor the state and changes of *D. octopetala*, and to investigate possible differences or similarities with the alpine site.

In contrast to my hypothesis, the height of *D. octopetala* was similar between the two sites, and there was no relationship between height and soil moisture. This could be due to the prostrate, mat-forming growth form of *D. octopetala* (Elkington, 1971), suggesting that it would be unrealistic to expect "unlimited growth". It is likely that *D. octopetala* has reached its maximum height, and thus, warming had no effect. It could have been more relevant to examine the height of flower shoots, as Welker et al., (1997) found that the flower shoot increased with higher temperature. In addition, height measurement of the entire vegetation, and not only *D. octopetala* could in the future paint a more cohesive picture of the vegetation response to warming.

4.2 Species richness and composition

There was no difference in species richness or composition between OTC warming plots and control plots in either location. However, there was a tendency for lower values regarding the Simpson diversity index (*D*) with warming in the alpine site, which was not observed in the High Arctic site, partially supporting my hypothesis. After 23 years of warming experiments in the alpine site, Eiterjord (2024) found that warming had a significant effect on species composition and that there was significantly higher species richness in control plots than in the OTC warming plots. My study had a small sample size as only ten plots were dominated by *D. octopetala* in the High Arctic site. However, a higher sample size might have resulted in a significant difference in diversity index with warming, at least in the alpine site given Eiterjords (2024) findings. Previous studies done in the alpine site have reported minor changes within community composition with warming. Indeed, Klanderud (2008) found that four years of warming did not affect community composition, and Hasvik (2018) found that only species richness of lichens and forbs was affected after 17 years of warming, whereas species composition did not differ between OTC warming plots and controls. Thus, long-term monitoring is important to capture the vegetation response to warming.

Control plots with high soil moisture had a higher cover of bryophytes and lichens in the alpine site, which is in line with numerous studies showing that the presence of bryophytes and lichens decreases with warming (Elmendorf et al., 2012a; Lang et al., 2012; Walker et al., 2006). OTC warming plots are known to decrease the soil moisture on drier sites, especially at surface level (Björnsdóttir et al., 2021; Bokhorst et al., 2013; Sjögersten & Wookey, 2002). The higher accumulation of litter within the OTC warming plots (Eiterjord, 2024) and the decrease in soil moisture could explain the significantly lower cover of bryophytes and lichens with warming in the alpine site. Increased nutrient availability with warming (Chapin III et al., 1995) would negatively affect bryophytes and lichens, and Klanderud & Totland (2005) found that warming combined with nutrient addition resulted in significant loss of bryophytes and lichens species, as well as their abundance.

Further, the species richness significantly increased as the *D. octopetala* got taller within control plots in the alpine site. Taller *D. octopetala* could function as a nurse plant, facilitating the establishment of other species (Callaway, 1995; Yarranton & Morrison, 1974) for instance by protecting the underlying vegetation against wind exposure (Carlsson & Callaghan, 1991). Wind protection is especially important at the beginning of the growing season when the snow cover is gone, but the ground is still frozen, and the vegetation is water-limited (Wilson, 1959).

On the other hand, the dense mat growth of *D. octopetala* could outcompete shade-intolerant species (Walker et al., 2006), and Klanderud & Totland (2004) found little evidence for nursing effects by *D. octopetala*. It is possible that the underlying vegetation is not yet light-limited and is benefitting from the additional sheltering from higher *D. octopetala.* However, this sheltering effect could eventually become more competitive with increased warming. In addition, small dwarf shrubs "catch snow" thus altering the distribution and persistence of snow cover (Liston & Sturm, 2002; Pomeroy et al., 2006; Sturm et al., 2005). Snow cover not only acts as an effective isolator and protects the vegetation from extreme wind and temperature exposure (Pomeroy & Brun, 2001), but it also increases the soil moisture after melt out (Cooper et al., 2019). In Northeast Greenland, Nabe-Nielsen et al. (2017) found higher species richness in areas with moist soil. Future studies should consider snow measurements to better monitor and increase the knowledge of changing winter conditions and snow melt, and how this affects the vegetation.

Unlike the alpine site, there was no tendency for differences in the Simpson diversity index with warming in the High Arctic site. It is important to note that the vegetation analysis in the alpine site recorded all species present within the plots, whereas in the High Arctic site, only species hit during the point-frame analysis were recorded, and species of bryophytes and lichens were not registered. Thus, it is highly likely that the total number of species present within the plots was higher than recorded. Nonetheless, High Arctic communities have previously shown less response to warming compared to lower Arctic communities (Hudson & Henry, 2010; Walker et al., 2006). The lack of difference in plant species richness and composition in the High Arctic site could be explained by the ambient temperature increase that has occurred since the site was established in 2001. In the High Arctic site, Vandvik et al. (2023) recorded a 0.62-1.67°C difference in the summer ground temperature between OTC warming plots and control plots. However, the mean annual temperature on Svalbard increased by 1.66°C per decade between 1991 and - 2018 (Nordli et al., 2020). Thus, the effect of experimental warming on the vegetation could be "drowned out" by the ambient temperature increase. Indeed, Jonsdottir et al. (2023) found that the plant species composition changed within both warming and control plots in the High Arctic site. The natural temperature increase and subsequent change in vegetation could thus mask or explain the lack of difference between OTC warming plots and control plots. This effect might be even more pronounced once temperatures reach beyond 10°C, where the vegetation does not benefit from further warming as a threshold is reached

(Elmendorf & Hollister, 2023), illustrating that the vegetation is changing, both with and without artificial temperature increases.

Conclusion

The alpine and the High Arctic sites exhibit different responses to warming when it comes to the cover of *D. octopetala* and greening. The results from this study indicate a possible tipping point for the *D. octopetala*. Warming has the potential of reaching an upper limit, pushing the species response beyond previous observation and predictions, potentially leading to *D. octopetala* being unable to adapt to the new conditions. There was a tendency for lower species diversity within the warming plot in the alpine site, which was not observed in the High Arctic site. Lower temperature areas, such as the High Arctic, are still in a stage of greening, responding to increased warming, where the response is higher with higher soil moisture. However, the High Arctic vegetation might face similar conditions as the alpine site as temperature continues to increase. My findings suggest that higher temperatures are not the sole driving factor for vegetation changes, and understanding the effect of warming on the tundra is still challenging, even with over 20 years of monitoring. A combination of several factors, such as soil moisture, nutrient availability, and competition, all contribute to changes in the vegetation with climate change. In conclusion, this study highlights the importance of local conditions on the effect of experimental warming on *D. octopetala* - dominated vegetation and how long-term monitoring is vital to understand the changes in the tundra vegetation as temperatures continue to increase.

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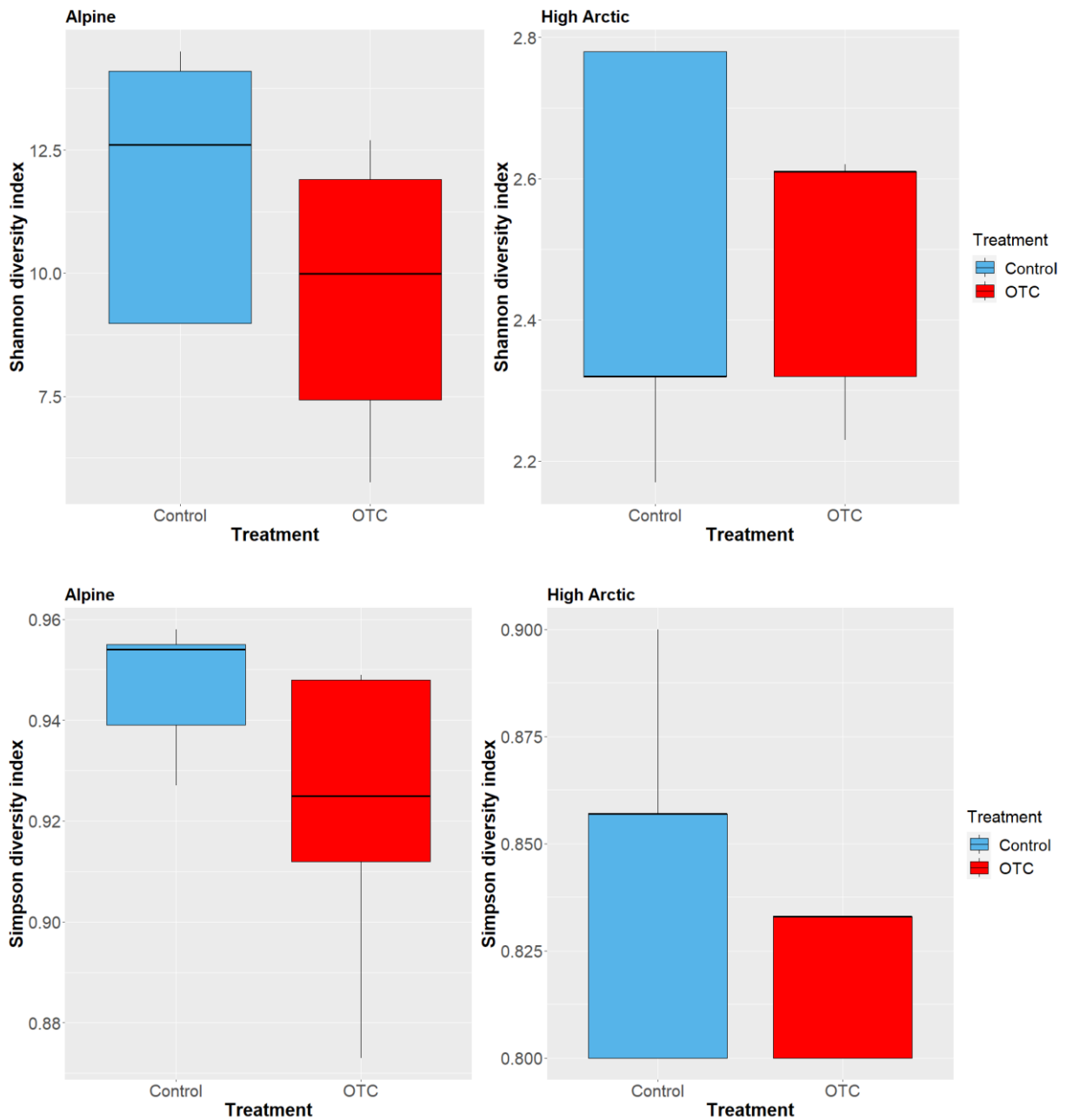
Appendix

Figure 12: The effect of treatment on the Shannon diversity index *H* (top) and the Simpson diversity index *D* (bottom) within the control plots (blue) and OTC warming plots (red) in the alpine site (left) and the High Arctic site (right). n=5 for both treatments. Note the different scaling on the y-axis.
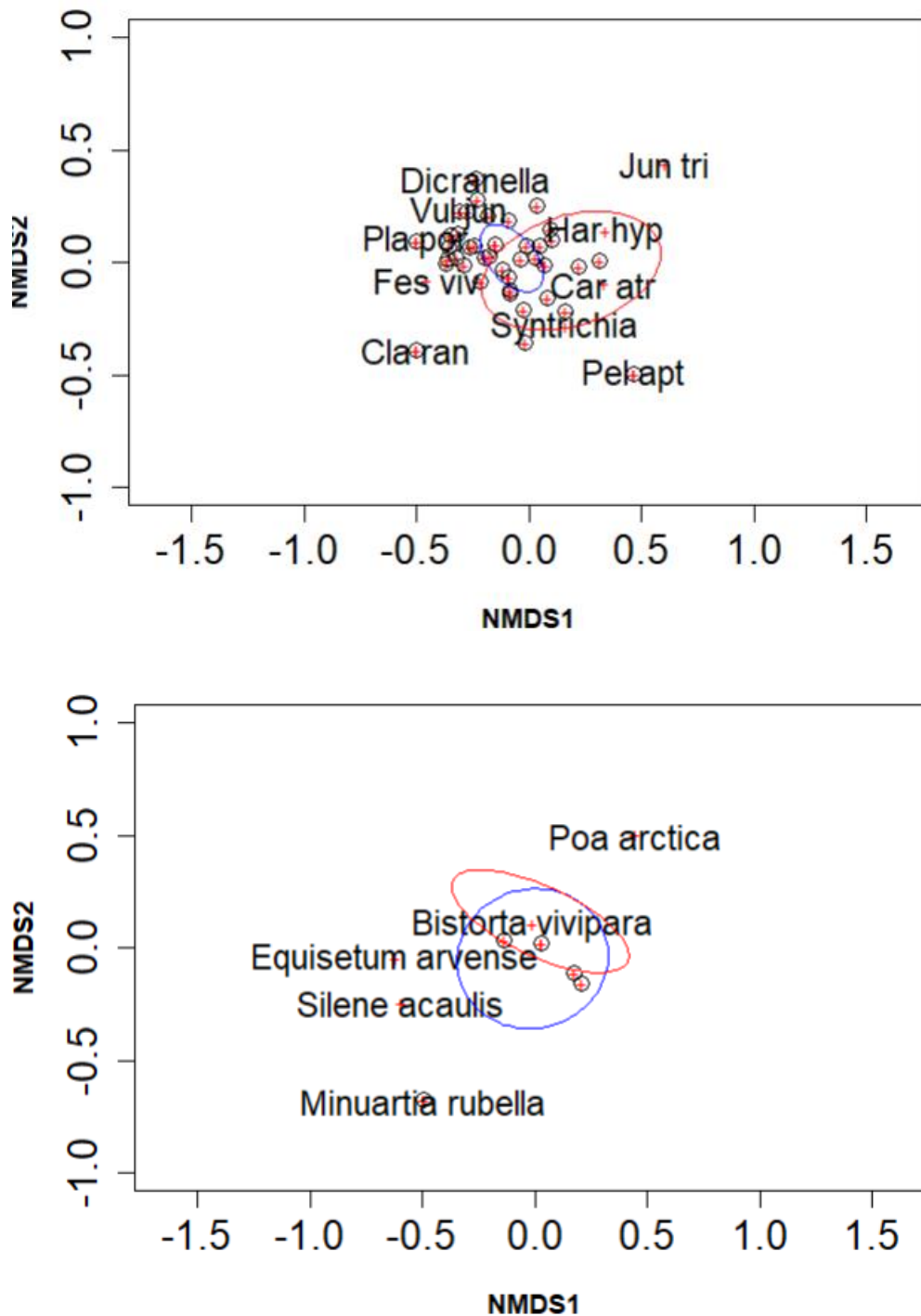
Figure 13: Distribution of some species along the two NMDS-axis for the alpine site (top) and the High Arctic site (below). The species plotted are what R-studio presents as non-overlapping when creating the plots. The blue ring shows the 95% confidence interval for control plots, whereas the red ring shows the 95% confidence interval for OTC warming plots.
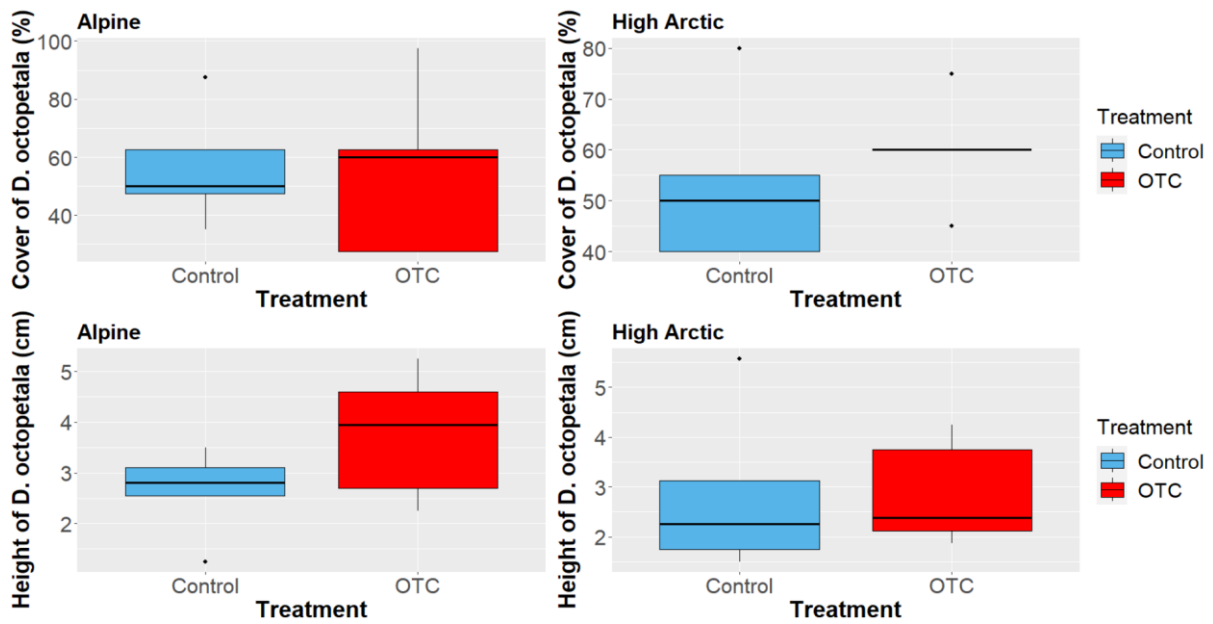
Figure 14: The effect of treatment on *D. octopetala* cover (above) and the height of *D. octopetala* (bellow) within the control plots (blue) and OTC warming plots (red) in the alpine site (left) and the High Arctic site (right). n=5 for both treatments. Note the different scaling on the y-axis.
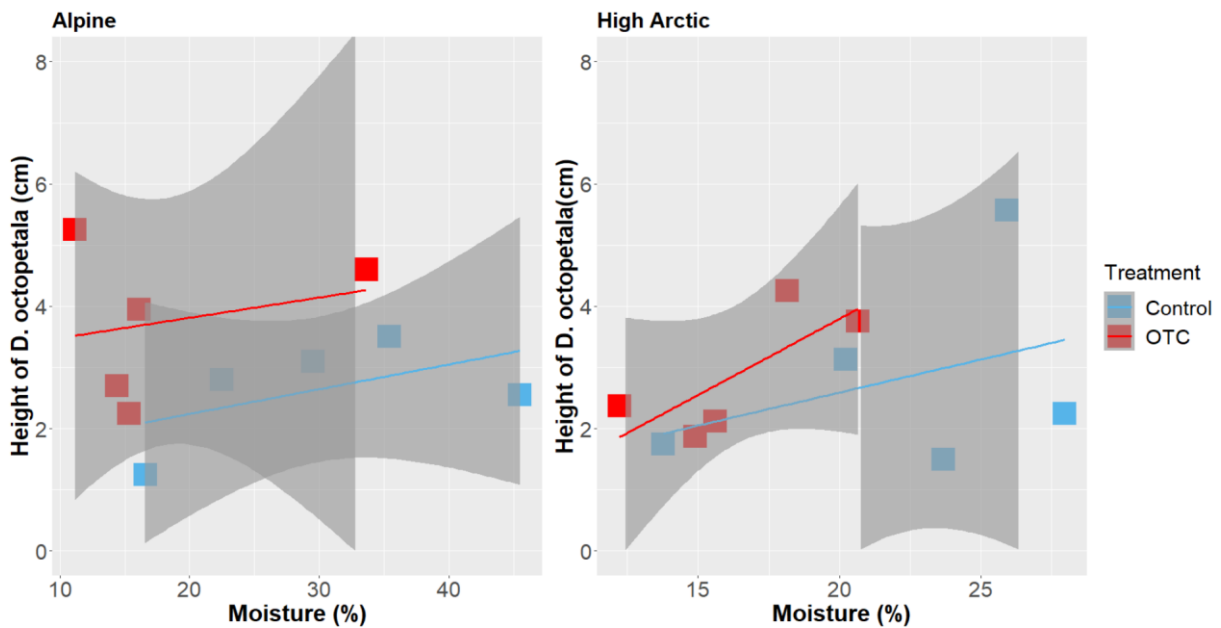

Figure 15: Height of *D. octopetala* plotted against soil moisture within the control plots (blue) and OTC warming plots (red) in the alpine site (left) and the High Arctic site (right). Grey area shows 95% confidential interval.
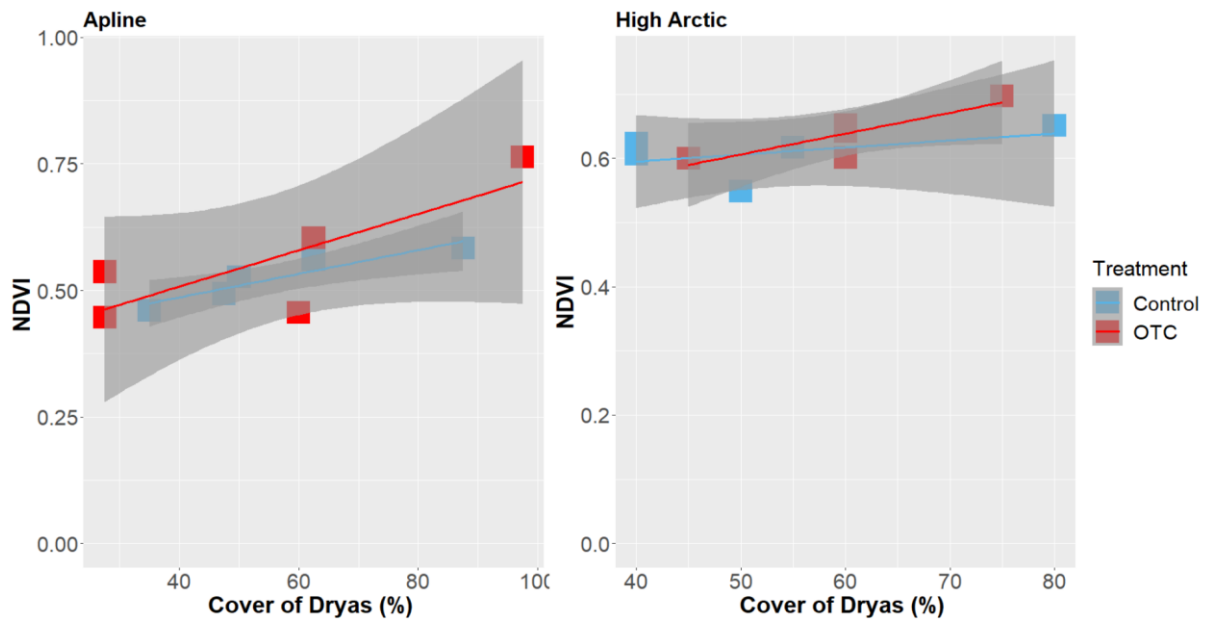
Figure 16: NDVI plotted against cover of *D. octopetala* within the control plots (blue) and OTC warming plots (red) in the alpine site (left) and the High Arctic site (right). Grey area shows 95% confidential interval. Note the different scaling on the y-axis.