Shrubs Effects on Soil Temperatures, Snow Depth, and Vegetation Greenness in Arctic-alpine Tundra

Alfred Bäckman

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Swedish University of Agricultural Sciences, SLU
Faculty of Natural Resources and Agricultural Sciences/Department of Soil and Environment
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Shrubs Effects on Soil Temperatures, Snow Depth, and, Vegetation Greenness in Arctic-alpine Tundra

Buskars påverkan på marktemperaturer, snödjup och grönska i arktisk alpin tundra

Alfred Bäckman

Supervisor:	**Eveline Krab, SLU, Mark och Miljö**
Examiner:	Katharina Meurer, SLU, Mark och Miljö

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Abstract

Arctic ecosystems experience rapid changes in temperatures due to climate-induced warming and as an effect, deciduous shrub abundance is increasing throughout the northern hemisphere. The expansion of tall shrubs can affect snow coverage, soil temperatures, nutrient cycles, and, in turn, the life cycle of many other arctic organisms. Since 2018, the project ALTER has experimentally removed vegetation with certain mycorrhizal connections from sub-arctic tundra heath in Abisko. In this study, I use data from the ALTER project alongside snow measurements made on April 24th, 2024 to explore how the removal of tall deciduous shrubs with ectomycorrhizal associations affects soil temperatures, greenness, snow depth, and, snow coverage compared to a no-removal control. Removal of tall shrubs showed no significant correlation, only trends affecting spring and summer temperatures. The removal did not affect snow depth or snow coverage with differences most likely dependent on other factors such as microtopography. Differences in greenness were not significant and most likely too small to show any meaningful results but did, however, highlight a need for extended greenness measurements to capture differences throughout the growing season. This study further emphasizes the need for long-term ecological research to gain insight into slow-moving ecological effects following climate change.

Abstract

Arktiska ekosystem upplever snabba förändringar i temperatur på grund av klimat-inducerad uppvärmning och som en effekt ökar förekomsten av lövfällande buskar över det norra halvklotet. Denna utbredning av höga buskar kan påverka snötäckning, marktemperaturer, växtnäringskretslopp och till följd livscyklerna hos många andra arktiska organismer. Sedan 2018 har projektet ALTER gjort experimentell borttagning av vegetation baserad på mycorrhizainteraktioner från subarktisk tundrahed i Abisko. I den här studien använder jag data från ALTER projektet tillsammans med egna snömätningar från den 24e April 2024 för att utforska hur borttagning av höga lövfällande buskar med ectomyccorhizala associationer påverkar marktemperaturer, grönhet, snödjup och snötäcke jämfört med en kontroll utan vegetationsborttagning. Borttagning av höga buskar visade ingen signifikant korrelation, endast trender mot att påverka vår och sommartemperaturer. Borttagning påverkade inte snödjup eller snötäcke och skillnader beror sannolikt på andra faktorer som mikrotopografi. Skillnader i grönhet var inte signifikanta och var till största sannolikhet för små för att visa något meningsfullt resultat. Resultatet uppmärksammade däremot ett behov för att utöka mätningarna för grönhet så att skillnader över växtsäsongen kan fångas upp. Den här studien betonar även nödvändigheten av långvarig ekologisk forskning som kan ge insikt gällande långsamma ekologiska effekter som följer klimatförändringar.

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Abbreviations

Table 1 List of abbreviations

ALTER	Abisko Long-Term Ecological Research
C	Carbon
CO_2	Carbon dioxide
EcM	Ectomycorrhizal
Gt C	Gigaton Carbon
N	Nitrogen
SLU	Swedish University of Agricultural Sciences
NDVI	Normalized Difference Vegetation Index (a proxy for greenness)

1. Introduction

The arctic ecosystem is very delicate and one of the areas of our planet most affected by climate change. Arctic air temperatures have doubled compared to the global averages during the last 20 years, with noticeable effects on vegetation, snow coverage, hydrology, and soil structure (Intergovernmental Panel On Climate Change (IPCC) 2022). These effects have significance to global CO_2 emissions as permafrost thaw is projected to release upwards to 240 Gt C as carbon dioxide or methane to the atmosphere by 2100. This could lead to negative feedback loops where increased carbon emissions directly caused by climate change further speed up global warming.

The rapid changes in temperature due to climate change have significant effects on arctic vegetation. Moreover, the IPCC report shows greening of the tundra biome, with an expansion of woody shrubs and trees projected to cover 24-52% of the region by 2050 (Intergovernmental Panel On Climate Change (IPCC) 2022). This change in plant composition from low herbaceous to tall deciduous plants is called Arctic shrubification and can affect the ecosystem by altering nutrient cycles, snow dynamics, and a very complex system of soil-plant-atmosphere interactions (Mekonnen et al. 2021).

One of the effects this shrubification has on the Arctic ecosystem is the way tall shrubs affect snow coverage and soil temperatures. Tall deciduous shrubs can trap more snow in their canopies which act as insulation against cold air temperatures during the winter, and increase winter soil temperatures (Vowles & Björk 2019). Tall shrubs can also lower summer soil temperatures because their large canopies provide shading from the sun (Lawrence & Swenson 2011). This cooling during the summer could positively affect permafrost cover. The increase in winter temperatures brought by shrubs' effect on snow coverage could offset the soil cooling and negatively impact permafrost. Studies have shown that soil temperatures are highly affected by the successional stages of shrubs with mature shrubland exhibiting higher winter and lower summer soil temperatures compared to tundra (Frost et al. 2018). Snow and its effect on winter temperatures is one of the biggest factors driving productivity in arctic vegetation, explaining the observed greening trends (Kelsey et al. 2021). Snow depth can also delay the timing of snowmelt which shortens the growing season, and higher temperatures have been shown to increase the availability of nutrients such as N and could compensate for the shortened growing period (Semenchuk 2013). This increase in N could be beneficial for deciduous shrubs and create a positive feedback loop where increased snow depth and warmer winter temperatures created by shrubs further improve their growing conditions (Frei & Henry 2022). These complex interactions between aboveground vegetation, snow coverage, and soil temperatures are important to study to understand how they affect each other and to predict future effects of shrubification.

Normalized Difference Vegetation Index (NDVI) is one of the most common ways of measuring greenness and vegetation health and is used in many studies concerning vegetational changes in the Arctic. Satellite data of NDVI show that photosynthetic activity has increased in northern regions, a sign that more productive vegetation is moving further north and snow cover is one of the most important factors affecting vegetation activity in the Arctic, especially concerning NDVI as snowmelt timing may affect the timing of maximum NDVI (Buus-Hinkler et al. 2006). Snowmelt timing is also an important part of the phenology of arctic vegetation and can affect reproduction and growth with differences in relative impact between species (Frei & Henry 2022). For example, snow blocks out incident photosynthetically active radiation (PAR), a form of visible light that induces plant development, and it protects plants from experiencing frost damage due to low air temperatures (Wu et al. 2023). This makes the role of snow in the life cycles of arctic vegetation quite significant and a necessary field of study concerning climate change.

Many studies have been made regarding the importance of snow depth and snow melt on the phenology of tundra vegetation, some of which applied snow fences to trap snow and create greater snow depths than those during normal conditions (Mörsdorf et al. 2019). Others studied naturally occurring microtopography which influences snow depth and timing of snowmelt to see its effects on vegetation distribution, nutrient availability, and phenology (Moriana-Armendariz et al. 2022). It would therefore be interesting to see how removal treatment based on mycorrhizal associations would impact snow depth, the timing of snow melt, soil temperatures, and phenology to gain further insight into the effects of further shrubification of the Arctic.

The study on which I will base my thesis is the ALTER (Abisko Long-term Tundra Experimental Research) project. In this experiment, plants are removed based on which mycorrhizal fungi they have formed symbiotic associations with. This generally corresponds to the removal of dwarf shrubs versus taller deciduous shrubs. The goal of the ALTER project is to gain insight into soil microbial and fungal communities and their long-term effects on soil C and N pools, as this pertains to aboveground changes to vegetation following arctic shrubification. Their results showed that on short timescales soil microbial communities have large buffering capacity despite large aboveground changes in vegetation, however, the long-term effects of shrubification and an advancing tree line on soil microbial communities are still unclear.

1.1 Aim and research questions

The thesis will be an extension of the ALTER project and focus on the effect of vegetational changes on snow depth, snow cover, and soil temperature as well as greenness. This study aims to further understand these effects in an environment highly affected by climate change.

The research question I pose is: will active removal of tall shrubs reverse the increased accumulation of snow and the following effects on greenness and soil temperatures that have been observed throughout the Arctic?

The hypotheses I set out to test are as follows: 1. Soil temperatures will decrease during the winter and increase during the summer following tall shrub removal. 2. Removal of tall shrubs will decrease snow depth and lower snow coverage. 3. Removal of tall shrubs will lower overall greenness. 4. A green pixel counting method could be a suitable alternative to NDVI as a measurement of greenness.

2. Method

2.1 Experimental design

2.1.1 Study site

The study site for this project is the same as the ALTER project (Kirchhoff et al. 2024), located in Abisko about 510m above sea level on a northwest-facing mountain slope a few kilometers southeast of the town of Abisko (7582398.766 N, 154082.577 E). The area vegetation type is classed as forest-tundra as it mainly consists of mountain birch (*Betula pubescens subsp. czerepanovii*), pine trees (*Pinus sylvestris*), and several species of *Salix* below the treeline. Above the treeline small shrubs, grasses and sedges dominate such as dwarf-birch (*Betula nana*), crowberry (*Empetrum nigrum*), lingonberries (*Vaccinium vitis-idaea*), bog blueberries (*Vaccinium uliginosum*) and bog rosemary (*Andromeda polifolia*). The reseach site is located below the tree line, in an area with vegetation resembling alpine (above treeline) tundra absent of *B. pubescens subsp. Czerepanovii.* Abisko receives the least amount of precipitation in Sweden with only 300 mm per year (*Regnskugga | SMHI* 2009), which makes it an interesting study site for snow coverage.

Figure 1 Picture of the study site taken on April 26th, 2024 (Alfred Bäckman)

2.1.2 ALTER

The ALTER project has studied different mycorrhizal associations and their effects on soil properties by using a plant removal method on a south-facing slope in Abisko since 2018 (Kirchhoff et al. 2024). Five spatially replicated blocks were set up, each containing eight plots. My study will only focus on six of these plots, a no removal control (CTL), ectomycorrhizal associated plant removal (EcM), and four non-specific removal-gradient plots of each block as they are relevant to my research question. The reason for having 5 spatially separated blocks is to be able to factor in natural deviance when analyzing differences between treatments. The CTL plot receives no removal treatment and is only dug out around the perimeter of the blocks to mark the edges. EcM removal plots receive trimming each summer season where plants listed as Ectomychorrizal (Table 2) are removed from the plots. In gradient plots, a grid mesh net is placed to section the plot into 100 0,2m squares, and between 0 – 100 % of the vegetation is removed. The amount of vegetation removed from each gradient plot can be seen in Table 3. Vegetation removal is done by light pulling by hand for smaller plants. For larger plants, the stem is clipped a few centimeters below ground to not disturb the soil. To see an extensive list of all plants removed see Appendix 1.

Table 2 Plant species removed from -EcM plots based on mycorrhizal symbioses.

Ectomyccorhizal
Betula nana
Dryas octopetala
Polygonum viviparium / Bistorta vivipara
Salix glauca
Salix hastata
Salix myrsinites
Salix phylicifolia
Salix reticulata

Table 3 Gradient plots % of vegetation removal

Block	Plot A	Plot B	Plot C	Plot D
1	60	85	5	0
2	0	100	40	20
3	15	65	0	30
4	45	0	75	10
5	50	25	0	90

2.2 Sampling and analysis

2.2.1 Soil temperature

Since the start of the ALTER project soil temperatures have been measured with HOBO loggers submerged in the ground. Loggers were placed in the centre of each 2x2m plot. Temperatures were logged every hour, 24 hours a day for all the days of the year starting in 2018. For the year 2019, blocks 3, 4, and 5 had missing loggers for plots with EcM removal. The logger for the CTL plot in block 1 stopped working during the year 2023. This is an extensive data series with five years of temperature data. To be used in my research it had to be compiled and mean daily temperatures were calculated using Microsoft Excel. Three aspects were selected to compare the temperature data for CTL and EcM plots. Firstly, the yearly average temperature and average temperatures of each season during each year. Seasons of interest were winter (November-February), winter/spring (March-May), and summer (June-August). The autumn season (September-October) was not included since it is not a part of either the growing season or season of snow coverage. Secondly, snowmelt dates were determined using the temperature data to see when temperatures rose above 1 °C after a stable period around 0 °C. Since melting snowwater stabilizes soil temperatures, preventing soil warming, a spike in temperatures following a "plateau" in the data can be used to expect when all the snow has melted (Krab et al. 2022). Thirdly the lowest and highest daily temperature values during the year of each plot were compiled.

2.2.2 Snow depth and snow coverage

On April 24th, 2024, snow depth was measured in all CTL and EcM treatment plots, 2 plots in each of the 5 blocks. Each plot is $2m^2$ and divided into 4 $1m^2$ subplots. A wooden stick marked each of the 4 corners of the plot. Two pieces of rope approximately 2,8m long were then used to mark two diagonal lines from the opposite-facing corners of the plot, forming a cross shape. The ropes then ran across the hypotenuse of each subplot and where the ropes crossed, marked the middle of the plot. Using these ropes as guidance 5 measurements of snow depth were made. In the middle of the plot and the middle of each subplot (see Figure 2), the depth of the snow was measured with a 2m yardstick. Where the snow had formed a hardened layer of ice, a bamboo stick was used to break the ice layer. Some plots were completely covered in a thick layer of snow where the ice layer made it difficult to penetrate. This fact made it hard to accurately measure the middle of each plot and subplot. The average snow depth of each plot was calculated using the 5 measurements.

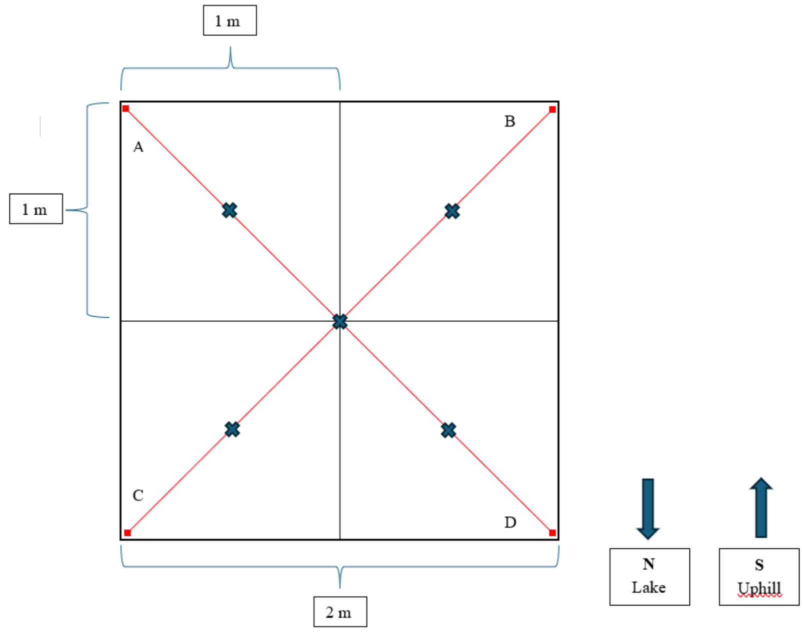

Figure 2 . Schematic of plot and marking for snow depth measurements. A, B, C, and D are the names of each subplot. X marks where snow depth measurements were made and the red lines represent the ropes used for guidance.

Pictures were also taken of each plot to measure snow coverage. The photos were taken from the same side on each plot, facing west with the lake on the right side and the mountain hill on the left. Pictures were taken with a compact camera from about 2m above the ground, trying to keep the same angle each time. These pictures were then analyzed using ImageJ to measure the amount of white pixels which gives a value of snow coverage on each plot. Plot pictures were cropped using the sticks marking the corners of each plot as guiding points. The image was made black and white by selecting “8-bit”. The threshold was set to 170-255 and applied to all pictures to highlight the white areas (snow covered) of the image. This was done manually by visually ensuring as much of the snow-covered areas were selected. Lastly, the particles were analyzed to count the number of white pixels in the image.

2.2.3 Phenology

To measure greenness phenology and how they differ between treatments preexisting pictures of each plot taken during the summer period of each year (2019-2023) were used. Measurement of greenness was made in the program

ImageJ by counting green pixels, for a step-by-step guide see Appendix 1. Plot pictures were cropped along shovel marks marking the edges of the plots. The image was then split into separate channels, (Red Blue, and Green). The green image was selected and a threshold was set to highlight the green areas of the image. This was done manually by thoroughly inspecting the original image and visually ensuring the green areas, (vegetation), were separated from the remaining parts e.g. exposed soil, measuring equipment, and dead plant parts. Threshold 95-220 was used for all images. Lastly, particles were analyzed to count the number of green pixels in the image. Because of the small amount and size of deciduous shrubs in the plots before removal, EcM plots still count as having 100% coverage and do not have to be corrected to account for general removal effects. As the plot pictures were taken for documentation and were not ideally suited for analysis, this issue gave rise to some error sources.

NDVI measurements were done on 4 dates during the summer of 2023: July 21st, July 26th, August 15th, and August 21st. NDVI analyses reflected red and near-infrared light and gave a value between -1 and +1 where higher values represent higher greenness.

To test whether the NDVI and green pixel measurements were suitable indicators of greenness, comparisons with the gradient plots were made for both. The percentage of vegetation coverage in the gradient plots ranges from 0-100%. If measurements of NDVI and green pixels correlate with the amount of vegetation coverage, it would indicate that the methods are well suited for analysis. These two greenness measurements were also compared to see how well the method of counting green pixels compares to the NDVI measurements (given that they provide a more reliable result). This was also done with measurements of gradient plots.

2.2.4 Statistical analysis

In the statistical analysis, using R-studio, linear models were used to look for correlations between the two treatments, CTL and EcM, for every output except for Snowmelt date, Snow depth and Snow coverage (Table 4). First, for each output measured a mixed model was made using the R-packages lme4 and lmerTest incorporating all factors: ‘treatment’, ‘block’, and ‘year’ (using plot ID as a random factor). This creates a powerful analysis of treatment effects. The full mixed model for NDVI was made using date instead of year. To test that a linear model was a suitable analysis method, each full mixed model was checked for homogeneity of variance using R-packages pbkrtest and multcomp.

Secondly, for each year t-tests were made to analyze all outputs without a block factor. To include block factors, individual two-way ANOVAs (Analysis of variance) were made for each output and year. Since there are replications in 5 spatially separate blocks, differences that depend solely on which block each treatment plot is located in could be accounted for using blocks as a fixed effect in the linear models. These individual tests were used to examine which years could explain the results of treatment effects in the mixed models. P-values presented in full mixed models are associated with an F-statistic (Pr(>F)) using Satterthwaite's method. F-values explain significant differences between the means of different groups. P-values less than 0.05 show significance and values between 0.05 and 0.1 are insignificant but might indicate some effect. For all results from the full mixed model see Appendix 1.

Table 4 Outputs and factors used for statistical analysis in R-studio

Outputs	**Factors**
Soiltemp yearly average	ID (random)
Soiltemp winter average	Block
Soiltemp spring average	Treatment
Soiltemp summeravg	Year
Lowest temp during year	Date (for NDVI)
Highest temp during year	
Snowmeltdate	
Snow depth	
Snow coverage	
Green pixels	
NDVI	

3. Results

3.1 Soil temperature

Statistical analysis did not show significance for the treatment effect on soil temperatures for any of the chosen aspects across the 5 years but gave some indications of relevance. The full mixed model for the effect of soil temperature during spring showed trends towards significance with treatment (F value 3,48, Pr(>F) 0,07), year (F value 3,79, Pr(>F) 0,06), and treat:year (F value 3,48, Pr(>F) 0,07). This means there were some variations in spring soil temperatures dependent on treatment but they were not consistent between years. Soil temperature during summer also showed trends for significance but for treat:block (F value 3,86, Pr(>F) 0,06) and treat:year:block (F value 3,85, Pr(>F) 0,06) indicating that there were effects of treatment but that they were not consistent between blocks and years.

When exploring the soil temperature data visually we can see a trend of -ECM plots having higher summer soil temperatures than CTL plots, especially in 2023 and 2021 (Figures 3 & 4). In Figure 3 it is also clear that there are differences in temperature between blocks within a year. This variation between blocks helps to factor out naturally occurring differences that affect the soil temperature and contribute to a more reliable result. Since the loggers for 2024 that were placed in July of 2023 have not been retrieved yet some data is missing from the remaining summer season of 2023. This could affect and possibly skew the result. Two-way ANOVA (Analysis of variance) showed a significant correlation for summer soil temperature with treatment (F value 34,706, Pr(>F) 0.001062), block (F value 12,010, Pr(>F) 0.013377) and, treat;block (F value 20,377, Pr(>F) 0.004043). This could explain the full mixed model results. However, the results may be unreliable since 3 -EcM plots were missing from 2019. Looking at Figure 4, most years show no difference between treatments in spring soil temperatures except for 2023 and 2019. The treatment effect is, however, different between the two years. -EcM treatment had lower average temperatures in 2023, and higher in 2019.

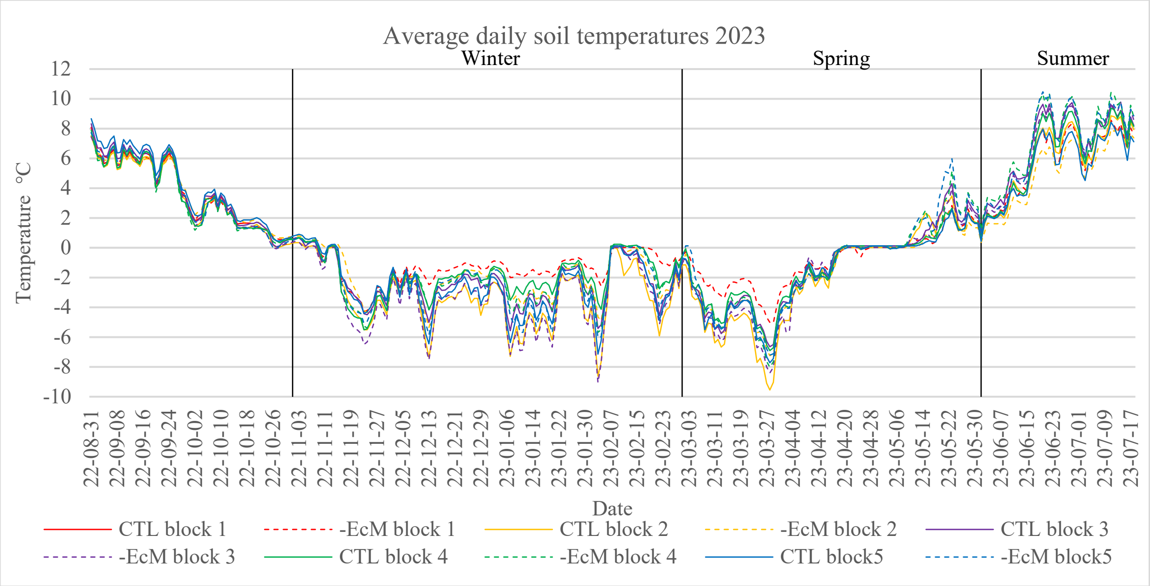

Figure 3 Average daily temperatures from logger data captured in 2022-2023. Loggers were placed in the plots on 2022-08-31 and retrieved 2023-07-18. The dotted lines represent -ECM treatments and the solid lines CTL. Each year is color coordinated. Vertical black lines separate the year into seasons and the name of each season is presented at the top (autumn excluded)

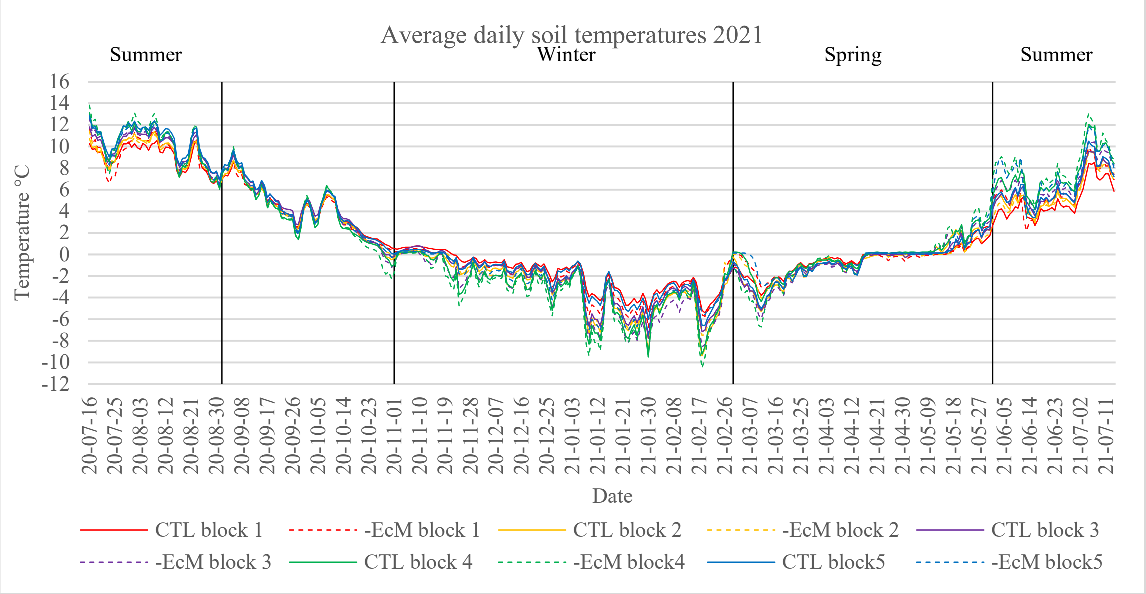

Figure 4 Average daily temperatures from logger data captured in 2020-2021. Loggers were placed in the plots on 2022-07-16 and retrieved 2021-07-11. The dotted lines represent -ECM treatments and the solid lines CTL. Each year is color coordinated. Vertical black lines separate the year into seasons and the name of each season is presented at the top (autumn excluded)

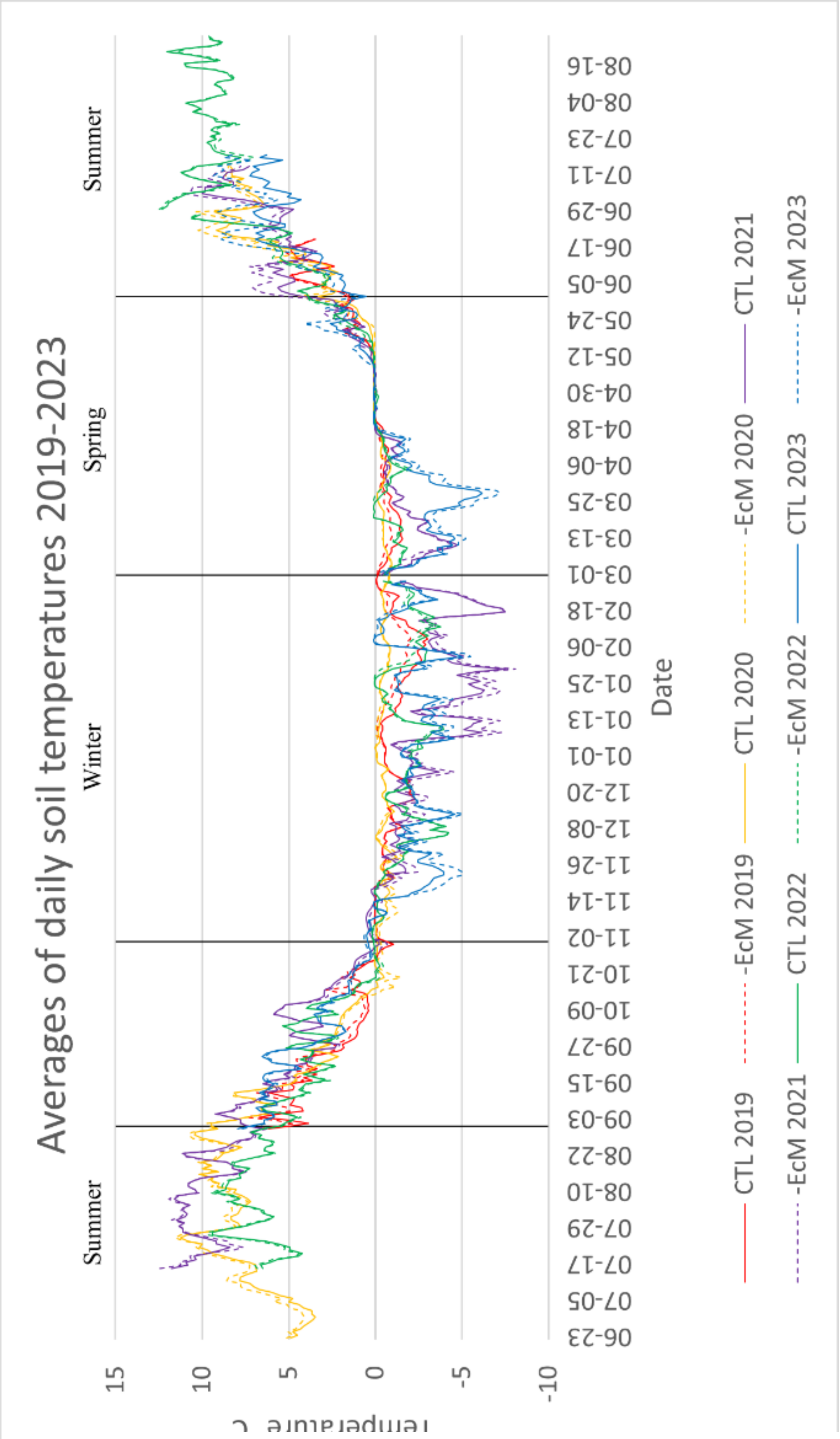

Figure 5 Averages of daily soil temperature for the year 2019-2023. The dotted lines represent -ECM treatments and the solid lines CTL. Each year is color coordinated. Vertical black lines separate the year into seasons, and the name of each season is presented at the top (autumn excluded)

3.2 Snow depth and snow coverage

There was a weak trend towards significance for an interaction between treatment with block factor (F-value 3.9836 and Pr(>F) 0.09295), for snow depth, which shows an effect of treatment on snow depth but that it was inconsistent between blocks. As shown in Figure 6 the differences in snow depth between plots were small except for two outliers, one of which was a CTL and the other a -ECM plot. Differences in elevation within blocks ranged from 1 to 4 meters and between blocks upwards to 10 meters, which could affect snow accumulation. No significant correlation was found between snow coverage and treatment. Figure 7 shows large differences between blocks and plots with no consistent treatment effect. This could also be due to the heterogeneity in the microtopography of the study site landscape, see Appendix 1 for pictures of the difference between blocks and plots.

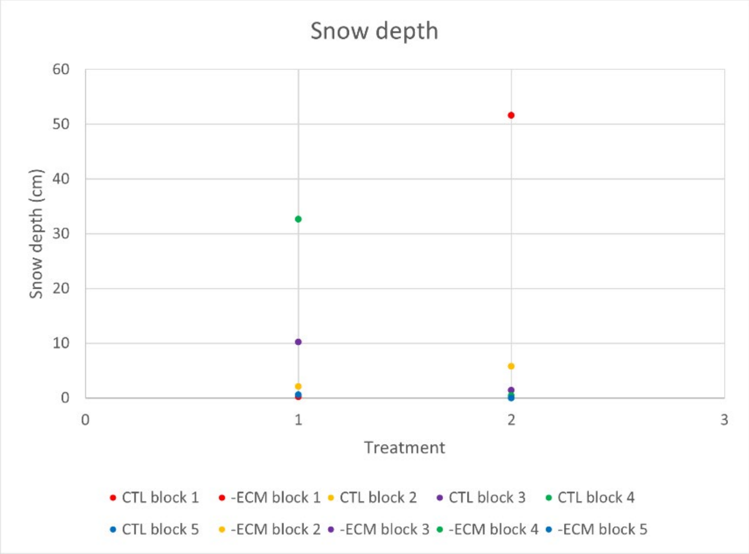

Figure 6 Average snow depth for each CTL and -EcM plot measured on April 24th, 2024. Averages are calculated using 5 points of measurement, one in each subplot and one in the middle of the plot. A value of 1 on the x-axis represents CTL plots and a value of 2 represents -ECM plots

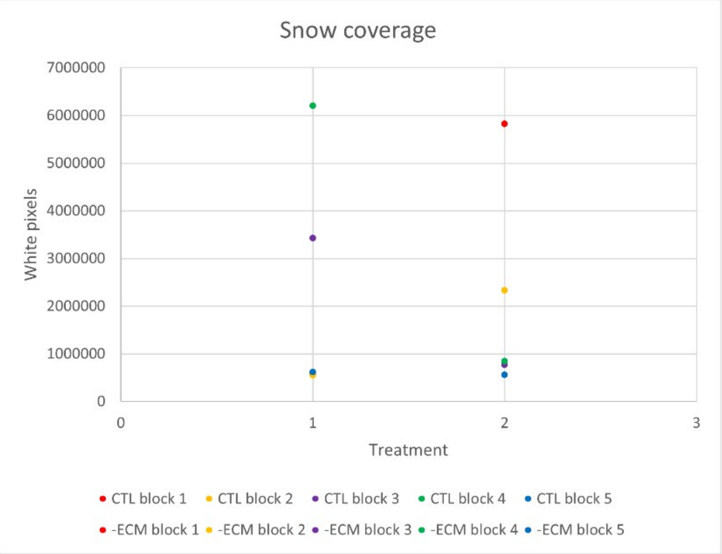

Figure 7 Snow coverage for each CTL and -EcM plot measured on April 24th 2024. A value of 1 on x-axis represents CTL plots and a value of 2 represents -ECM plots

3.3 Greenness phenology

Full mixed model statistical analysis of the difference in treatment effect on NDVI did not show significance, only that there was a significant difference between the four dates of measurement (Pr (>F) 0.03) and between the blocks (Pr (>F) 0.01). This was to be expected since the blocks are different from each other and the vegetation is in different phenological stages during the summer. It did, however, show a potential peak of season in greenness phenology that was not originally expected. The peak of season refers to the point of the growing season in which plants exhibit the highest greenness and when they start to lower their photosynthesis. NDVI values were lower on August 21st than on July 21st and highest on July 26th which indicates that the peak of season for greenness could be late July to early August rather than late August (Figure 8). This could be useful for future NDVI measurements in the ALTER experiment as it would require tests being made earlier during the summer to get measurements for the full scope of the growing season.

There was a statistically significant correlation between NDVI and % cover on gradient plots. This fact shows that NDVI is a good measurement of greenness and that results in the analysis of CTL and EcM treatments are reliable (Figure 9).

As for the analysis of green pixels, there was no significant correlation with % coverage for the gradient plots which could indicate that the method of counting green pixels is a less suitable measurement for greenness. Green pixels showed a significant correlation with NDVI for July 21st, 2023 (Figure 10), suggesting that it could potentially be trusted as a comparable metric in measuring greenness phenology. These two contradicting correlations with green pixels do nonetheless bring some uncertainty to the viability of the pixel counting method.

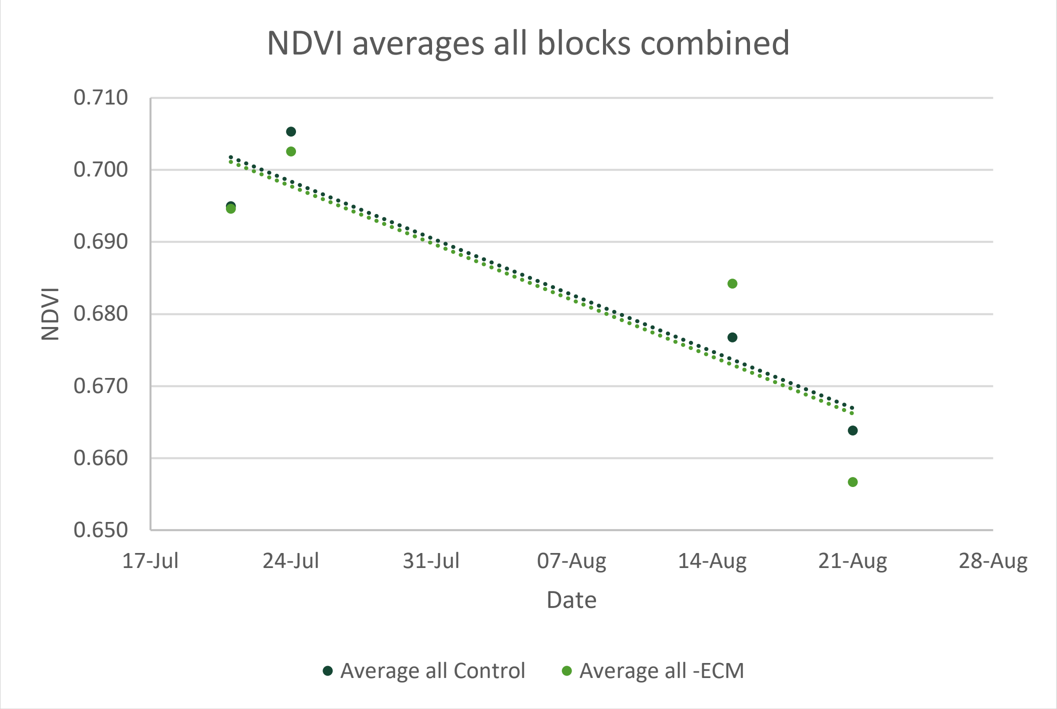

Figure 8 Average NDVI measurements for -EcM and CTL treatment plots in 2023. Measurements were taken at four dates, July 21st, July 26th, August 15th, and August 21st.

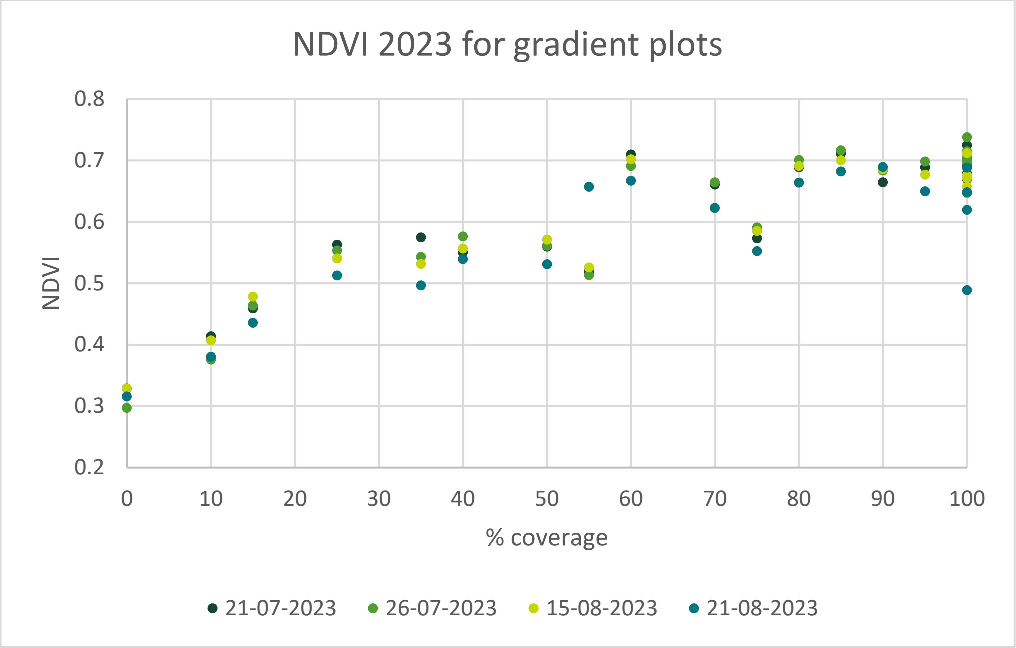

Figure 9 NDVI vs % coverage for gradient plots on each of the 4 dates of measurements during summer of 2023.

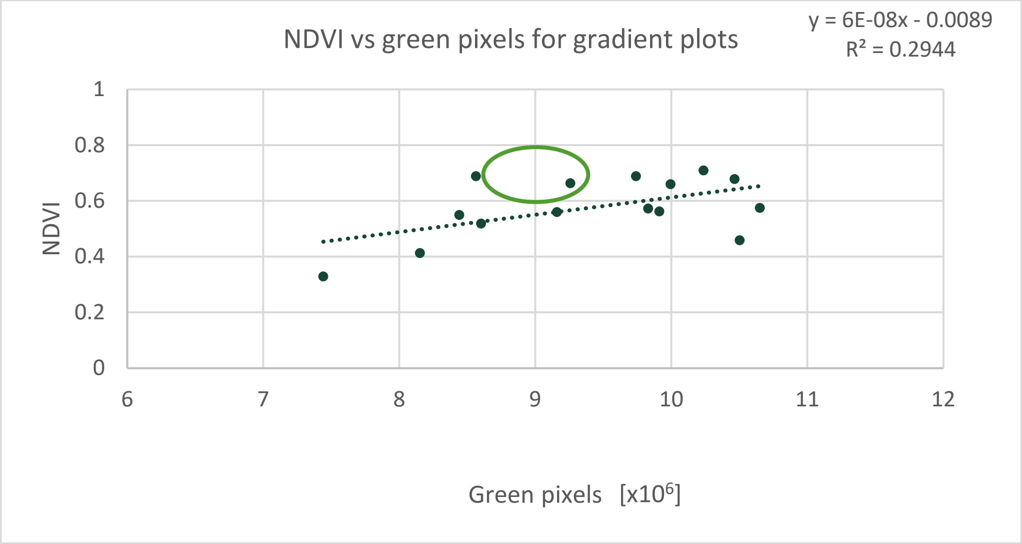

Figure 10 NDVI vs green pixels for gradient plots on July 21st. The green circle shows the approximate location for treatment plots (around 9 x 10^6 pixels – 0,7 NDVI)

4. Discussion

4.1 Soil temperatures

Results showed no significant correlation between tall shrub removal treatment and soil temperatures, only trends suggesting that my first hypothesis may be true. I hypothesized that the removal of tall shrubs would decrease winter temperatures and increase summer temperatures. The trends found showed that this might be the case, although the results were not consistent across all years and for summer temperatures not between blocks either.

These trends align with results from similar studies, which indicate that tall shrubs can lower summer temperatures due to shading from the canopy (Lawrence & Swenson 2011). This could explain why summer temperatures were higher in plots where EcM plants were removed. A study from Siberia showed that mature shrubs decreased summer soil temperatures by 9 °C compared to open tundra (Frost et al. 2018). The largest shrubs present at the study site, *B. nana,* were relatively small (<0,5m) and the effect of its shading might be quite small due to its low stature but still enough to point towards lower temperatures. The mature shrubs in this Siberian study were more than 2m high which gives a significantly stronger effect on snow and shading.

Soil moisture also affects soil temperatures. Taller shrubs that consume more water contribute to dryer soils which can lead to cooler winter temperatures (Lawrence & Swenson 2011). This could lead to tall shrubs having antagonistic effects on soil temperatures and might explain the insignificant results. Wet tundra vegetation found in shallow depressions is shown to experience higher summer temperatures due to its higher moisture contents, which also coincides with increased snow accumulation during the winter (Szymański et al. 2022).

Soil temperatures follow air temperatures more closely in tundra without tall shrubs because of the lack of insulating snow (Frost et al. 2018). This raises an interesting point of view not accounted for in my study. How air and soil temperatures align could potentially give insight into fluctuations in snow coverage during the year and between blocks.

4.2 Snow depth and snow coverage

No correlation was found between treatment and snow depth or snow coverage. A weak trend suggests some differences between treatments for snow depth but does not coincide with my second hypothesis. I expected snow depth to be lower in plots where tall shrubs were removed. The results show that the effect of treatment was different in different blocks, i.e, some blocks show higher snow depth after removal while other blocks show lower snow depth. It would be interesting to have more extensive data on the changes in snow depth throughout the season. This would give a clearer picture of how the snow changes are affected by the treatments. As my results are contradictory, the dataset might be too small to give tangible results. A large source of errors is that there was no time to duplicate these measurements. Repeated measurements of snow depths across the winter and spring seasons would be required to see any true effects of the removal treatment on snow depth and snow coverage. Ecological effects are often slow and certain effects following removal might be visible on a longer timescale than this study can include.

One factor that plays a major part in snow accumulation is microtopography, such as natural depressions, which were not accounted for in this research. Natural differences in microtopography strongly affect snow coverage, snowmelt timing, and in turn phenology as well, which creates a heterogenous landscape that may become more homogenous as temperatures rise and snow coverage decreases (Moriana-Armendariz et al. 2022). The difference between blocks, and between plots within each block, majorly affects how much snow coverage each plot has. This was noticeable during the fieldwork as there was a clear disparity that seemingly had nothing to do with the treatments of the plots. Blocks located further down on the hillside had more snow coverage than the blocks that were located higher up. Other abiotic factors such as wind and the slope of the ground also affect the accumulation of snow on a greater scale than the removal treatments. Abiskos' low levels of precipitation could also affect the result since snow accumulation is much lower than in other locations. The deepest snowpack in this study was 51,6 cm compared to 120 cm, 150 cm, or upwards to 2m in other studies researching snow effects on soil temperatures, nutrient status, soil invertebrates, and vegetational composition (Convey et al. 2015; Mörsdorf et al. 2019; Moriana-Armendariz et al. 2022).

4.3 Greenness phenology

Even though -EcM plots had slightly lower NDVI values than CTL, the effect of removing deciduous shrubs was too small to show any significance. The deciduous shrubs found at the test site are generally quite small. This could contribute to the insignificant differences in NDVI and green pixels. As for the changes in greenness across the growing season, green pixels were only counted at one date per year and NDVI 4 dates in July and August. Having several measurements from the start until the end of the growing season could potentially give some interesting results regarding the changes in greenness between treatments as differences may be visible at different stages of the season. Earlier snowmelt and warmer spring temperatures have been suggested not to extend the growing season but rather shift it earlier (Kelsey et al. 2021). Higher spring soil temperatures are the driving factor of green-up but the effect differs between plant species (Krab et al. 2018).

Contrarily, areas with greater snow coverage and later snowmelt can experience a reduction in average NDVI and the overall length of the growing season (Buus-Hinkler et al. 2006). This shortening of the growing season can also shift the NDVI optimum so that the peak of the growing season is delayed (Meltofte 2002). Mid-season NDVI-values have been shown to vary greatly between different natural snowmelt regimes as the plants experiencing later snowmelt at their peak of growing season while plants with earlier snowmelt had passed theirs (Moriana-Armendariz et al. 2022). This difference in NDVI could potentially be linked to higher levels of nutrients in the late-regime plant leaves and shows that snow depth also affects NDVI across the season. Since results showed that NDVI peaked in late July to early August, extending NDVI measurements to start as early as the snow melts would catch differences caused by the difference in the date of snowmelt.

4.4 Other implications

Soil temperatures, snow effects, and greenness phenology are closely intertwined and affect each other in complex ways. They also affect other parts of their ecosystem that are important to discuss. Warmer winter temperatures and earlier snowmelt can lead to higher rates of nutrient cycling during the summer (Broadbent et al. 2022), and deeper snow regimes result in higher rates of available N in the soil that might surpass summer demands of arctic vegetation and microbes (Mörsdorf et al. 2019). Winter temperatures due to changes in snow insulation can affect the activity of soil microbes such as bacteria and fungi, which in turn affects the vegetation. On the other hand, snow removal has been shown to negatively affect soil microbial communities due to increased freeze-thaw events which lowers biological soil activity and the proportion of soil C (Broadbent et al. 2022). Soil microbial communities have shown resilience to aboveground vegetational changes over a short time scale (Kirchhoff et al. 2024). How fast shrubification will affect microbial communities over longer periods of time is still unclear.

Temperatures can also directly affect plant and invertebrate communities. As different species have different tolerance to changing temperatures, experimental warming has been shown to decrease plant species richness while increasing the dominance of certain invertebrates with higher tolerance for temperature changes (Robinson et al. 2018). Snow also blocks sunlight and can prevent vegetational growth which means that later snowmelt delay the start of phenological events such as green-up, flowering, and seed dispersal (Semenchuk et al. 2016). Soil temperatures affect when invertebrate species emerge from hibernation and earlier snowmelt can create a mismatch between plants and their pollinators (Kudo & Cooper 2019). The complex interactions between soil temperature and snow effects can therefore not only affect different organisms but also the interactions between them.

5. Conclusion

Even though this study found no statistically significant effects of tall shrub removal on soil temperatures, greenness, snow depth, or snow cover it does point towards results found in similar studies. Soil temperatures fluctuate between years and are highly affected by aboveground conditions. Snow accumulation can be dependent on vegetation, but microtopography may have a larger effect on areas with overall low vegetational heterogeneity. Changes in greenness between treatments are insignificant but treatment could affect the timing of greenup. It also highlights that changes following tall shrub removal are slow and insignificant on a short time scale and that longer-term perspectives are necessary when investigating changes following vegetational changes.

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Appendix 1

Step-by-step guide for green pixel counting in ImageJ

1. Open ImageJ and open the picture you want to analyze
2. Use “Polygon selections” to mark the area of the plot
3. Go to “Edit” and select “Clear outside”
4. Go to “Image” and select “Fill”
5. Go to “Image” and select “Color” and “Split channels” to split the image into red blue and green
6. Highlight the picture named (green), go to “Image” and “Threshold”
7. Move the sliders to highlight the pixels of interest, in this case the green pixels. Check with the original picture to make sure all green areas are highlighted. Then click “Apply”.
8. Go to “Analyze” and “Analyze particles”. Select the size of the particles you want to include in you analysis, “Show – Nothing”, and check boxes for “Display results”, “Summarize”.
9. The “Summary” window then shows pixel count (separate connected areas of green pixels), total area (actual number of individual green pixels), average size of the areas of green pixels, and %Area green pixels cover (this also includes the black outer edges if the plot picture isn’t perfectly square).

Table 1 Mixed model results for all outputs, made in R-studio

Kolumn1	output	F value	Pr(>F)	Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
treat	soiltemp_yearavg	1,35	0,25	
year	soiltemp_yearavg	2,32	0,14	
block	soiltemp_yearavg	2,37	0,13	
treat:year	soiltemp_yearavg	1,35	0,25	
treat:block	soiltemp_yearavg	0,04	0,84	
year:block	soiltemp_yearavg	2,37	0,13	
treat:year:block	soiltemp_yearavg	0,04	0,84	
treat	soiltemp_wintavg	1,24	0,27	
year	soiltemp_wintavg	1,52	0,23	
block	soiltemp_wintavg	0,19	0,67	
treat:year	soiltemp_wintavg	1,24	0,27	
treat:block	soiltemp_wintavg	0,25	0,62	
year:block	soiltemp_wintavg	0,17	0,68	
treat:year:block	soiltemp_wintavg	0,25	0,62	

treat	soiltemp_springavg	3,48	0,07	.
year	soiltemp_springavg	3,79	0,06	.
block	soiltemp_springavg	0,49	0,49	
treat:year	soiltemp_springavg	3,48	0,07	.
treat:block	soiltemp_springavg	0,05	0,83	
year:block	soiltemp_springavg	0,47	0,50	
treat:year:block	soiltemp_springavg	0,05	0,83	
treat	soiltemp_summeravg	0,35	0,55	
year	soiltemp_summeravg	0,13	0,72	
block	soiltemp_summeravg	0,56	0,46	
treat:year	soiltemp_summeravg	0,36	0,55	
treat:block	soiltemp_summeravg	3,86	0,06	.
year:block	soiltemp_summeravg	0,62	0,44	
treat:year:block	soiltemp_summeravg	3,85	0,06	.
treat	min.temp.during.year	0,46	0,50	
year	min.temp.during.year	0,41	0,53	
block	min.temp.during.year	1,12	0,30	
treat:year	min.temp.during.year	0,46	0,50	
treat:block	min.temp.during.year	0,18	0,68	
year:block	min.temp.during.year	1,12	0,30	
treat:year:block	min.temp.during.year	0,18	0,68	
treat	max.temp.during.year	0,03	0,85	
year	max.temp.during.year	0,62	0,44	
block	max.temp.during.year	0,16	0,69	
treat:year	max.temp.during.year	0,03	0,85	
treat:block	max.temp.during.year	1,02	0,32	
year:block	max.temp.during.year	0,16	0,69	
treat:year:block	max.temp.during.year	1,02	0,32	
treat	greenpix	0,00	0,95	
year	greenpix	0,00	0,94	
block	greenpix	0,10	0,75	
treat:year	greenpix	0,00	0,95	
treat:block	greenpix	0,05	0,82	
year:block	greenpix	0,10	0,75	
treat:year:block	greenpix	0,05	0,82	
treat	Snowmeltdate	0,42	0,52	
year	Snowmeltdate	0,29	0,60	
block	Snowmeltdate	0,70	0,41	
treat:year	Snowmeltdate	0,42	0,52	
treat:block	Snowmeltdate	0,97	0,33	
year:block	Snowmeltdate	0,72	0,40	
treat:year:block	Snowmeltdate	0,97	0,33	
treat	NDVI	0,00	0,99	
date	NDVI	5,51	0,03	*
block	NDVI	9,90	0,01	**
treat:date	NDVI	0,02	0,89	
treat:block	NDVI	0,00	0,96	
date:block	NDVI	0,33	0,57	

treat:date:block	NDVI	0,00	0,99

Table 2 Vegetation present before removal and their mycorrhizal associations

Species	**Mycorrhizal type**	**New spp. 2019**	**Mycorrhizal type**
Betula nana	Ectomycorrhiza	*Astragalus alpinus*	non
Empetrum nigrum	Ericoid	*Astragalus frigidus*	?
Vaccinium uliginosum	Ericoid	*Bartsia alpina*	non
Vaccinium vitis-idaea	Ericoid	*Calamagrostis lapponica*	non
Cassiope tretragona	Ericoid	*Carex bigelowii*	non
Polygonum viviparum	Ectomycorrhiza	*Carex vaginata*	non
Andromeda polyfolia	Ericoid	*Festuca ovina*	Arbuscular
Salix phylicifolia	Ectomycorrhiza	*Nardus stricta*	Arbuscular
Salix reticulata	Ectomycorrhiza	*Pedicularis lapponica*	non
Salix hastata	Ectomycorrhiza	*Tofieldia pusilla*	Arbuscular
Salix glauca	Ectomycorrhiza		
Salix myrsinites	Ectomycorrhiza		
Rhododendron lapponicum	Ericoid		
Dryas octopetala	Ectomycorrhiza		
Arctostaphylos alpinus	Arbutoid		
Pyrola rotundifolia	Arbutoid		
orchid spp.	Orchid		

Figure 1 Picture shows the method for snow depth measurement

Figure 2 CTL plot in block 4

Figure 3 -EcM plot in block 4

Figure 4 Block 5

Figure 5 Block 4

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