Geothermal soil warming responses of two common subarctic grassland plant species

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Abstract

Climate change, in particular the rising air temperature, will affect the dynamic and structure present in natural ecosystems. One of the consequences is a higher soil temperature. Researching the effects of a warmer soil on ecosystems and specifically plant species broads our understanding of these effects. These effects will be stronger in arctic ecosystems so this effect is being studied in natural geothermal soil temperature gradients in Iceland. This study aimed to see how a warmed soil, the weather and the soil water content affect the plant water status of two common Icelandic grassland species Agrostis capillaris and Ranunculus acris. This has been done my measuring the soil temperature, rainfall, air temperature, soil water content and plant water status in a geothermal soil warmed research site on the hills of Hveragerði, Iceland. The main findings were that the plant water status decreases significantly in plots with a relative high soil temperature for both Agrostis and Ranunculus. The phenomenon of a decreasing plant water status correlated overall strongly with a decline in the soil water content. Although the proven effect, the implications for arctic ecosystems are limited. The soil temperature in the researched plots was high and not realistic for natural arctic ecosystems. On top of that, no critical low levels of plant water status indicating water stress were reached by both plant species. The results suggest no immediate threat but further research is still valuable and needed, because arctic ecosystems' vulnerability to climate change is relatively high.

Keywords: *plant water status, soil water content, geothermal soil warming, subarctic grasslands*

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Glossary

ForHot
Scientific research site in Hveragerði, Iceland where natural soil warming in natural grasslands is being studied. The grasslands are being warmed by geothermal heat which results in temperature gradients with different average soil temperatures.

Plant water status - PWS (bar)
The plant water status (plant water potential) is the potential energy of water relative to water in atmospheric conditions. It causes a pressure that transports water from the soil to the leaves of a plant. The plant water status reflects the plants’ response to soil water supply and atmospheric demand.

Soil water content - SWC (%)
This thesis uses the volumetric soil water content to be precise. It is the volume of water per unit volume of soil expressed in a percentage.

Warming level - WL (°C)
A category assigned to a study plot in the ForHot research site. The warming level is the mean annual temperature in the plot on top of the ambient temperature. The warming levels are classified with a letter ranging from A (ambient) to F (warmest, +20 °C).

1 Introduction

The higher concentration of CO_2 in the atmosphere has been changing the climate significantly in the last century. That is especially noticeable in the colder climates in the arctic where an increase in temperature has a relatively large impact on nature (Parry & Carter, 1984; Global Annual Mean Surface Air Temperature Change, 2022). The harsh conditions of northern ecosystems with low temperatures, short growing season and limited nutrient availability, make plant communities vulnerable to even minor changes that are predicted under modest climate change scenarios (Kremers, Hollister, and Oberbauer, 2015). Due to climate change, the rise in temperature leads to stronger fluctuations in the water content and changes the heat balance in the soil. A warmer soil is one of the consequences.

This soil warming is important to study because it changes abiotic factors in the soil that influence vegetation growth and development. An increasing soil temperature means that plants will react differently to environmental variables. Some known changes in soils are among others a change in the soil moisture, pH, and decomposition rate (Sigurdsson et al., 2016). Soil warming can result in periods with drier soil or an increase in pH. This can lead to water stress, too acidic soils, or more general: less favourable site conditions for plants to live in. This can affect the primary production or development of a species which may lower its population and allows other species to colonize or suppress native plant species (Mooney & Hobbs, 2000). When certain plant species are less abundant, this may affect the food supply or habitat for other organisms dependent on those plant species. The abundance and diversity of plant species, are the building blocks for entire ecosystems and are vital for maintaining population dynamics (Berner et al, 2005). Soil warming will affect the balance in the ecosystem and the plant community structure (Meynzer, 2017). Soil warming can disrupt a stable balance in an ecosystem and increase vulnerability (IPCC, 2022). In what magnitude this occurs is still largely unclear and is valuable to be researched.

Natural areas are often less accessible where society can less easily experience these changes and consequences of climate change. The effect climate change has on agricultural land is much more tangible and economically more noticeable. However, the negative effects are not only present in places we can experience directly. We should care and know what is happening in these nature areas of the world because in the long term, a disrupted and damaged ecosystem will negatively affect our livelihood and quality of life (EEA, 2010).

Research has been done on the effects of soil warming on ecosystems, and in more detail, the effects on plant species. These effects are for example photosynthesis, metabolome, nutrients, and functional traits (Gargallo-Garriga et al., 2021., Meynzer, 2017). However, the relation between the intensity of soil warming, the weather, the soil water content, and how that specifically translates to the plant water status (PWS) has not been researched before. This is an interesting trait to study, because, according to Nehemy et al. (2019, preprint), "The plant water status reflects the plants' response to soil-water supply and atmospheric demand driven by water potential gradients …". Possible signs of drought that will translate to water stress for the plant can be shown by measuring the PWS.

To better understand the consequences of soil warming on ecosystems, this research will look into plant species and how they are affected by soil warming. It will do so for a case study in an Icelandic grassland where geothermal soil warming takes place. For this research, two plant species will be studied, Agrostis capillaris and Ranunculus acris. The objective of the research is to analyse the effect geothermal soil warming has on two common plant species in subarctic Icelandic grassland ecosystems. The following general research question has been formulated with accommodating specific research questions.

General research question

How does a warmed soil temperature gradient, the weather and soil water content affect the plant water status of two common Icelandic grassland species Agrostis capillaris and Ranunculus acris?

Specific research questions

1. How does the weather (air temperature and rainfall) change over a short-term geothermal soil warmed temperature gradient?
2. How does the soil water content change over a short-term geothermal soil warmed temperature gradient?

In the next chapter, the methodology and materials will describe the location where the research took place and how these questions were researched. Hereafter, the results will be presented with all the collected data on the research site. The results will be discussed and put into perspective supported by literature. At last, a conclusion will synthesize the thesis.

2 Method and materials

2.1 Study site

Iceland is an arctic country situated in the north of the Atlantic Ocean. The climate in Iceland is characterized by an average temperature of 8,1 degrees Celsius in the spring and summer months (April to August (Icelandic Met Office, n.d.). This means that plants usually grow in low temperatures. However, in May 2008, an earthquake hit South-Iceland that measured 6.3 on the Richter scale (ANSS, 2008). One of its many implications was that natural geothermal systems close to its epicentre were disturbed, causing the soil temperature to increase in new locations (Agricultural University of Iceland, 2021).

Some of these new geothermally warmed locations are on the hillsides around the town of Hveragerði in South Iceland. These locations are managed by the Agricultural University of Iceland and are also where the field work of this thesis has taken place ((64.0065°N, 21.1754°W; 83-168 m a.s.l.). Sigurdsson et al. (2016) characterize the research site as follows: "The recently warmed area is an unmanaged treeless grassland dominated by Agrostis capillaris grass, some herbs and moss, hereafter termed "GN" (Grassland New). The soil type is a Silandic Andosol (IUSS Working Group WBR 2015; a volcanic soil type, also known as Brown Andosol; Arnalds, 2015). It is silty loam in texture and it has the typical characteristics of such soils in Iceland (Arnalds, 2015)". The soil in GN is on average 38,3 cm deep but the soil depth is higher in the colder plots and shallower in the warmer plots (Sigurdsson et al., 2016). The recent soil warming situation has been made the core of a project and its research sites (ForHot) as it offers an interesting case study with experimental research potential.

Soil warming studies have been done before but the ForHot research site is a specific, natural and large-scale situation to study the effects of soil warming on an ecosystem at many different levels.

Another given of the study site is that the soil warming has also been ongoing since 2008. This makes this study unique, more accurate, and relevant for seeing the future consequences of soil warming on specific plant species and ecosystems.

It must be mentioned that the situation in the ForHot research site is not a perfect simulation of climate change. One of the relevant differences is that the soil warming is not gradual but happened suddenly. In addition, the geothermal warming affects the soil but has very little effect on the air temperature so these two factors are almost independent, whereas in climate change they would be coupled (Sigurdsson et al., 2016).

2.2 Experimental setup

Perpendicular to the soil temperature gradient in GN, three transects of fifty meters long were placed with each containing six permanent study plots (Figure 1). The size of the plots is 2 x 2 meters and the F plots are 1 x 1 meter. The temperature of the six plots range from ambient (A) to roughly +1 (B), +3 (C), +5 (D), +10 (E) and +20 °C (F) higher in average yearly soil temperature. These plots are also referred to as 'warming levels' (WLs). These WLs are not completely stable and may change from year to year

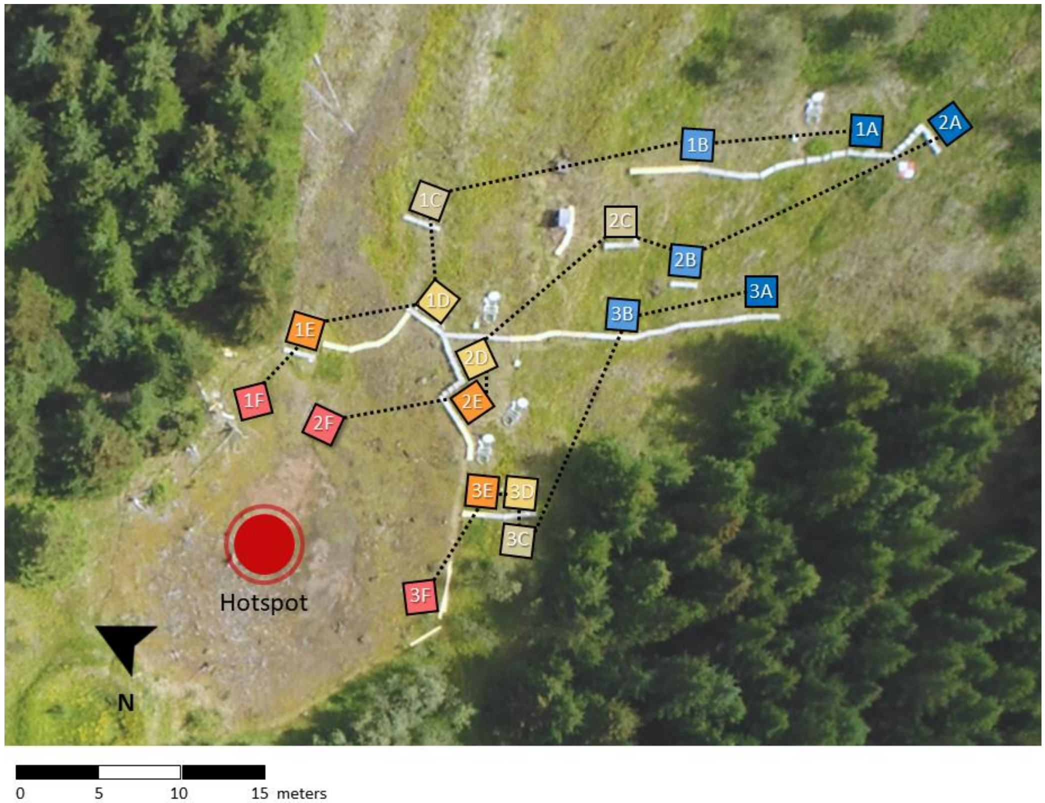

Figure 1 - Aerial photo of research site including the 3 transects. Each transect contains 6 standardized plots with warming levels ranging from ambient (A) to +20°C (F). The light lines are wooden boardwalks in the research site.

2.3 Plant species

The plants that have been studied in the warmed grassland ecosystem are Agrostis capillaris and Ranunculus acris. The targeted species are abundant in all the plots of the research site. These were selected as they are among the key species found in Icelandic grasslands and represent different categories (monocots & dicots, grasses & herbs) which make this a relevant and interesting selection to research (Gargallo-Garriga et al., 2017). By choosing these species, the result of this thesis can be carefully extrapolated toward other ecosystems in Iceland or other arctic regions. Further, related research on the effects of soil warming in Iceland has already been done on these plant species (Michielsen, 2014; Perron, 2017).

2.4 Field measurement

Environmental variables were measured during the growing season in Iceland. The growing season starts around the beginning of May and lasts until the end of September, but the measurements were carried out from mid-April to mid-July. The measured variables in this thesis are soil temperature, soil water content, and plant water status. In addition, air temperature and rainfall data from a weather station located 2,5 km (64.0263°N, 21.1975°W) from the study sites, have also been used to add more information about the local climate conditions.

The soil temperature was measured every hour adjacent to each plot with a HOBO TidbiT v2 Water Temperature Data Loggers. This was done at 10 cm soil depth. The volumetric soil water content was measured weekly from mid-April to mid-July. An ML3 ThetaProbe in combination with an HH2 Moisture Meter was used for this measurement which measures the soil water content at a soil depth of 5 cm. All the measurements were done in one day. This was done in the GN ecosystem in all five transects in all the plots from A-F. To not disturb the plants and soil in the plot for many other ongoing measurements, the soil moisture content using the ThetaProbe was measured on the border of the plot. For each measurement, a small patch of vegetation was removed from the topsoil to make sure the water content of the soil was measured and not part of the thick vegetation layer.

The plant water status (midday plant water potential) of both plant species was measured once every two weeks from early May to mid-July. A Model 615D Pressure Chamber Instrument from PMS Instrument Company was used. Pressure chamber measurements, in the context of this thesis, are very prone to errors when not used correctly regarding the time of day, weather conditions, and user operation. The PWS in the A, D, and E plots in the three transects in GN was measured 7 times. When a certain plant species was measured in a WL, at least 15 individuals were taken to minimize the error. To measure the midday plant water potential accurately, the measurement should take place around midday which is approximately at 13:30 in May, June, and July in Hveragerði (Pérez-Harguindeguy et al., 2016; Time and Date AS, n.d.). Since the total time of measurements can be quite long, measurements started at 10:30 and ended before 16:30. During this time period, the order of measuring the plots and species was randomized to eliminate a possible bias for the morning or afternoon. Measurements were carried out on days with stable weather and no expected rainfall. When all planned measurements could not be completed in one day, the day after was also used sometimes, only under the circumstances that the weather and the time were the same. This was to ensure consistent measurements.

3 Results

3.1 Soil temperature and weather

As described in the methodology, the Agrostis and Ranunculus plants grow in a grassland ecosystem in which the soil was being warmed by geothermal heat. This means that the plots A to F had a different mean soil temperature over the research period (April, May, June, and July). The A (ambient) plots had a mean temperature of 8,4 °C and the B, C, D, E and F plots had a mean temperature of 9,5; 11,8; 28,2; 39,4; and 39,8 °C (Figure 2). This made the B, C, D, E and F plots have a warming level of +1,1 (B); +3,4 (C); +19,8 (D); +31,1 (E); +31,4 °C (F). The warming levels of these four spring and summer months were higher compared to the mean annual temperature (MAT) measured in 2020 and 2021. The detailed data for these years can be found in Annex 1. The average temperatures of the last three years with the corresponding warming amounts are shown in table 1.

Table 1 - Average soil temperatures at 10 cm depth in GN plots A, B, C, D, E, F in the study period (April, May, June, and July 2022) and the 2 previous complete years (2021&2021) for comparison. For each period, the WL in relation to the A plot has been calculated.

	A	B	C	D	E	F
2022 (April-July)	8,4	9,5	11,8	28,2	39,4	39,8
Warming amount	0	+ 1,1	+ 3,4	+ 19,8	+ 31,0	+ 31,4
2020 & 2021	4,8	4,9	7,7	9,0	18,3	28,6
Warming amount	0	+ 0,1	+ 2,9	+ 4,2	+ 13,5	+ 23,8

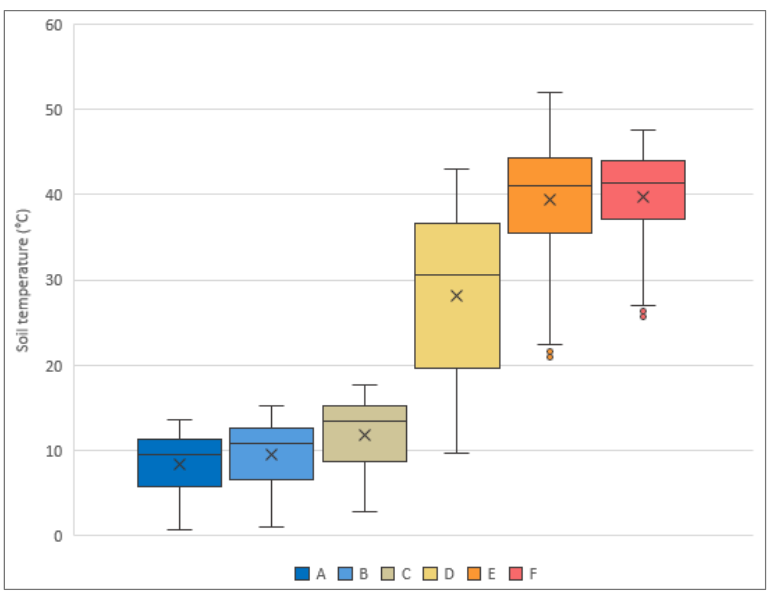

Figure 2 – The average soil temperature in plots A, B, C, D, E, and F visualized in a box plot in combination with the variability in the data set.

These soil temperature fluctuations during the study period were driven by the geothermal heat of the bedrock layer beneath the soil and the local weather conditions. Air temperature and rainfall have been measured and are shown in Figure 3 and 4. Like the normal climate in Iceland, the temperature difference between the summer and the winter was not that large. After a short frost period in the first week of April, the air temperature gradually increased. During the study period, the average temperature was 8,1 °C. The total rainfall during the study period was 557 mm. This fell quite uniformly throughout the four months. There were two noticeable light drought periods and some more heavy rain days which deviated from the regular pattern.

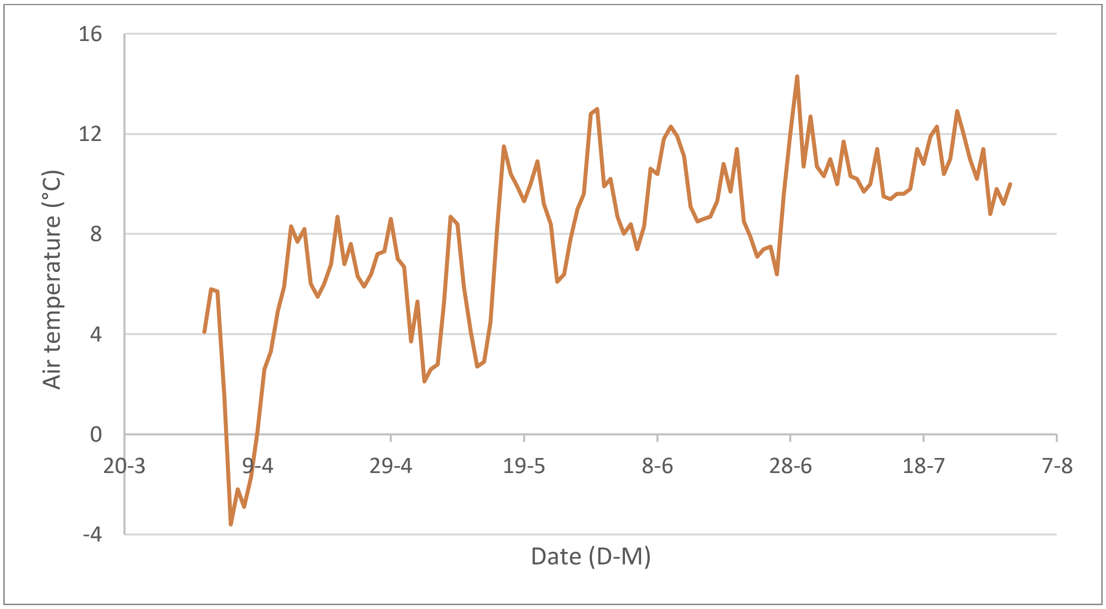

Figure 3 - Average daily temperature (°C) as a function of time in Hveragerði.

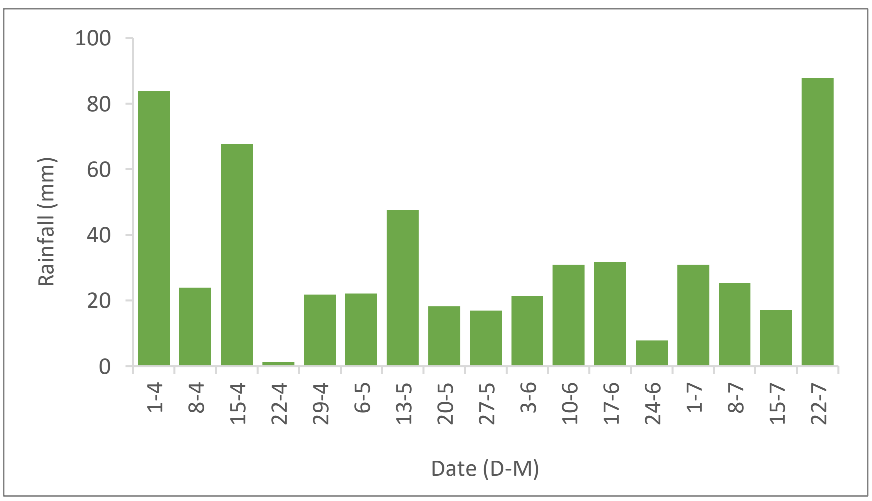

Figure 4 - Weekly total rainfall (mm) in Hveragerði.

The weather (in this case consisting of air temperature and rainfall) influenced the soil temperature. The soil temperature in the A, B, and C plots rose slightly (Figure 5) and were not too far apart from each other: 8,4; 9,5; 11,8 °C average temperatures. The warmer D, E, and F plots were not that much warmer in the beginning of the study period but increased in temperature much faster than the colder plots leaving a big difference between the plots (Figure 5). The data also showed that on average the E and F plots had very similar average soil temperatures throughout the study period (Figure 2). The D, E, and F plots showed a somewhat different warming level than what was expected compared to previous years (Table 1). The average temperatures per transect were not always close to each other and the variation was large. The standard deviation for the A, B, and C plots was on average 3,7 °C while for the D, E, and F plots, it was 7,5 °C. These more detailed graphs for each transect can be found in Annex 2. Another trend was that the soil temperature, also in the warmer D, E, and F plots, strongly fluctuated compared to the colder plots. According to B.D. Sigurdsson (personal communication, September 22, 2022) these temperature drops were because of relatively cold rain water infiltrating the soil. This relationship is very clear when combining the rainfall graph with the soil temperature as shown in Figure 5. The effect of rainfall, and the difference in temperature increase with time are the reasons why the variability in Figure 2 is higher in the warmer plots.

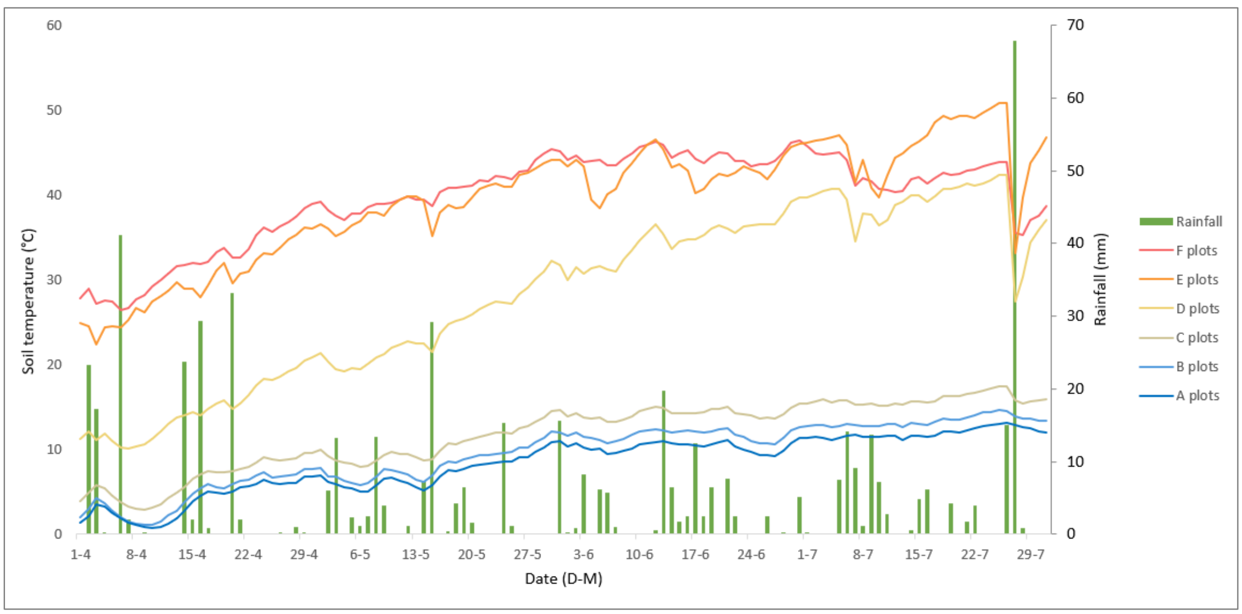

Figure 5 - Daily average soil temperature (°C) as a function of time in the A, B, C, D, E, and F plots in combination with the daily total rainfall (mm) in Hveragerði.

3.2 Soil water content

The air temperature, rainfall, and soil temperature influenced the soil water content (SWC). Soils in Iceland are usually wet which was also the case in the three transects in GN. It was found that the SWC in the study site was almost always above 30% with few exceptions (Figure 6). Overall, the colder A, B, and C plots mostly had a higher soil water content than the warmer D, E, and F plots. The rainfall influenced the main trend for the SWC. The slight drought period between June 23 and July 4 correlates with the clear soil water content drop in the second to last measurement moment seen in Figure 6, although not every small rainfall period is as visible in the graph as the week of April 22.

The standard deviation for these measurements was on average 5,8% per measurement moment between the replicates of each WL and was about equal for all the WLs. This SD is lower compared to previous years with volumetric water content measurements done in the same study site (Sigurdsson et al., 2016). The result of the average soil water content of all the WL of every transect is shown in Figure 7.

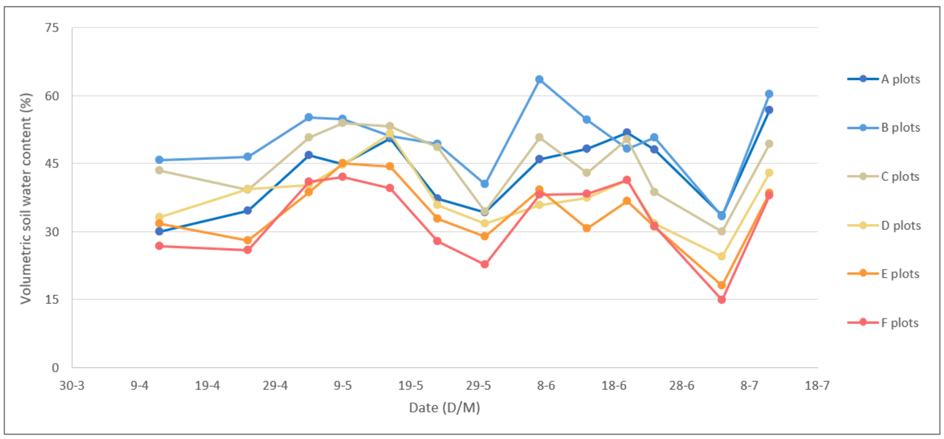

Figure 6 - Soil water content (%) as a function of time in the A, B, C, D, E, and F plots.

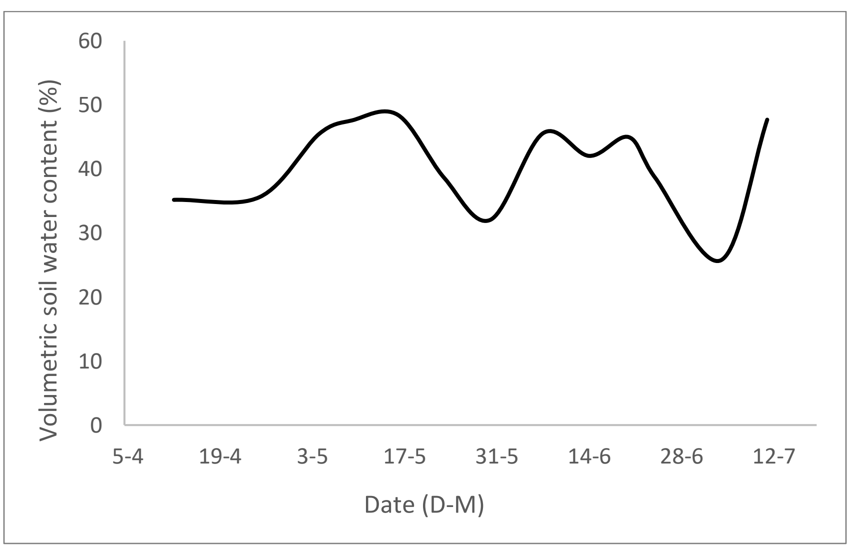

Figure 7 - Average soil water content (%) of all WLs (plots A, B, C, D, E, F) as a function of time.

3.3 Plant water status

As mentioned before, air temperature and rainfall affect the soil temperature. These three factors partially influence soil water content and all together, they affect the growth of Agrostis and Ranunculus in the soil warmed grassland ecosystem. The plant water status is a way to interpret this relationship, notably of the water balance. During the study period, six measurement moments have taken place where plant individuals from A, D, and E plots have been measured.

For both Agrostis and Ranunculus, the plant water status values of the D and E plots were comparable (Figures 8 and 9). So, for every measurement moment when the D and E plots were measured together, a two-sample t-Test assuming equal variances ($\alpha = 0,05$) was performed. The results are shown in Annex 3. The statistical tests showed that for every measurement moment, there was no significant difference between the PWS values of the D and E plots. This means that the PWS values for the D and E plots can be combined and will be considered as the same treatment.

For Agrostis (Figure 8), the differences between the values for the A and D/E plots were small. A statistical two-sample t-Test assuming equal variances ($\alpha = 0,05$) showed that although this small difference, the A and D/E plots were significantly different (Annex 3). The difference was the largest during the last measurement moment on July 4 where the A plots had less water stress than the Agrostis individuals in the D/E plots. When looking at all the values, the overall trend was that the values lowered as the season progressed.

Ranunculus (Figure 9) had a more constant PWS value throughout the season and indicated a slight decrease at the end of the season. Just like Agrostis, the difference in PWS values between the A and D/E plots was small. A two-sample t-Test assuming equal variances ($\alpha = 0,05$) also proved that there was a significant difference between the treatments every time. The A plots had a higher value at the end of the study period with also a small difference on the last measurement moment on July 4.

For both plant species, the last measurement moment on July 4 was different compared to the rest of the study period. The A and D/E plots all reached their lowest plant water potential value. This was especially the case for Agrostis where the drop was very clear. This was also at the end of the slight drought period at the end of June.

It should be noted that the measurement error per plot per measurement moment was on average 2,2 for Agrostis and 1,6 for Ranunculus.

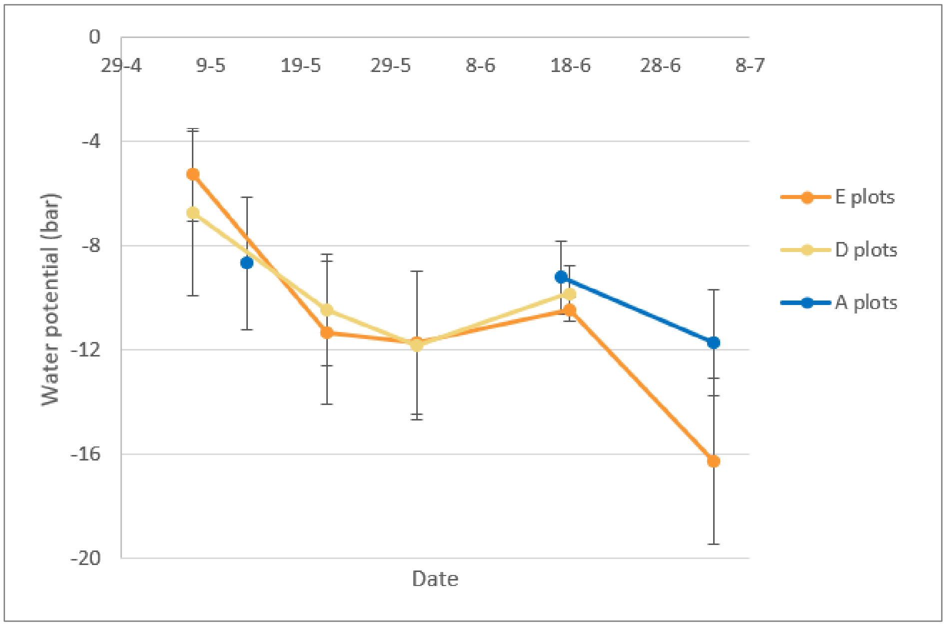

Figure 8 - Change in plant water status (bar) of Agrostis capillaris in the A, D, and E plots over time with standard deviation error bars.

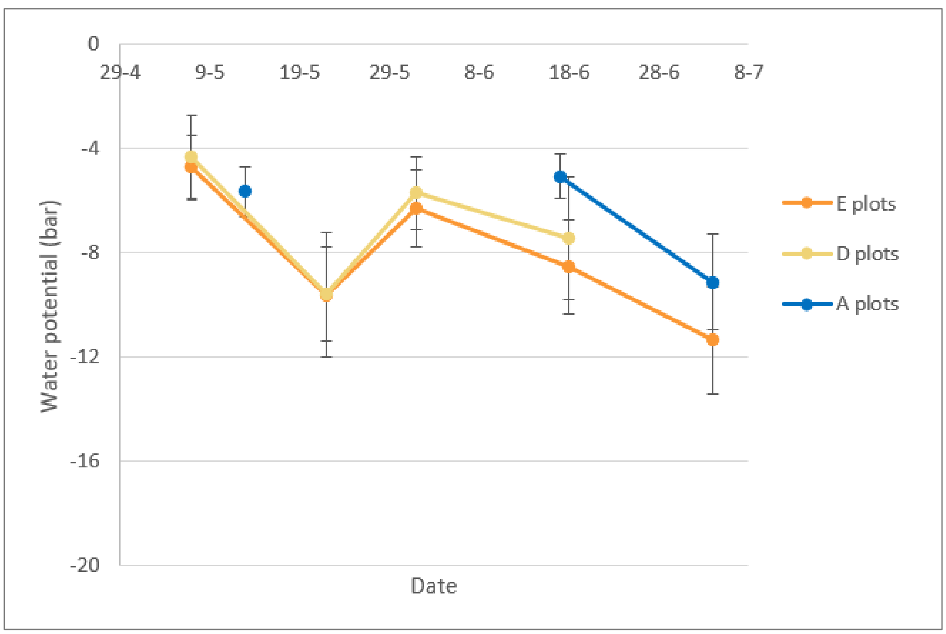

Figure 9 - Change in plant water status (bar) of Ranunculus acris in the A, D, and E plots over time with standard deviation error bars.

3.4 Correlation between soil water content and plant water status

The plant water status of both plant species is correlated to the soil and weather conditions. The soil water content and the plant water status are two variables that seem logical to correlate. When plotting these two variables, the correlation is visible. For Agrostis and Ranunculus, the water potential of the A plots (3 observations) and the D/ E plots (5 observations) have been plotted as a function of the soil water content on the same day. The specific SWC for that day has been interpolated between two measurement moments. The results are shown in Figure 10. Here it shows that the mentioned correlation for Agrostis was significant and strong with R^2 being 0,93 and 0,95 for the A and D/E plots respectively. The correlation for Ranunculus was also significant and strong for the A plots with R^2 = 1,00. The correlation was weaker for the D/E plots where R^2 = 0,56.

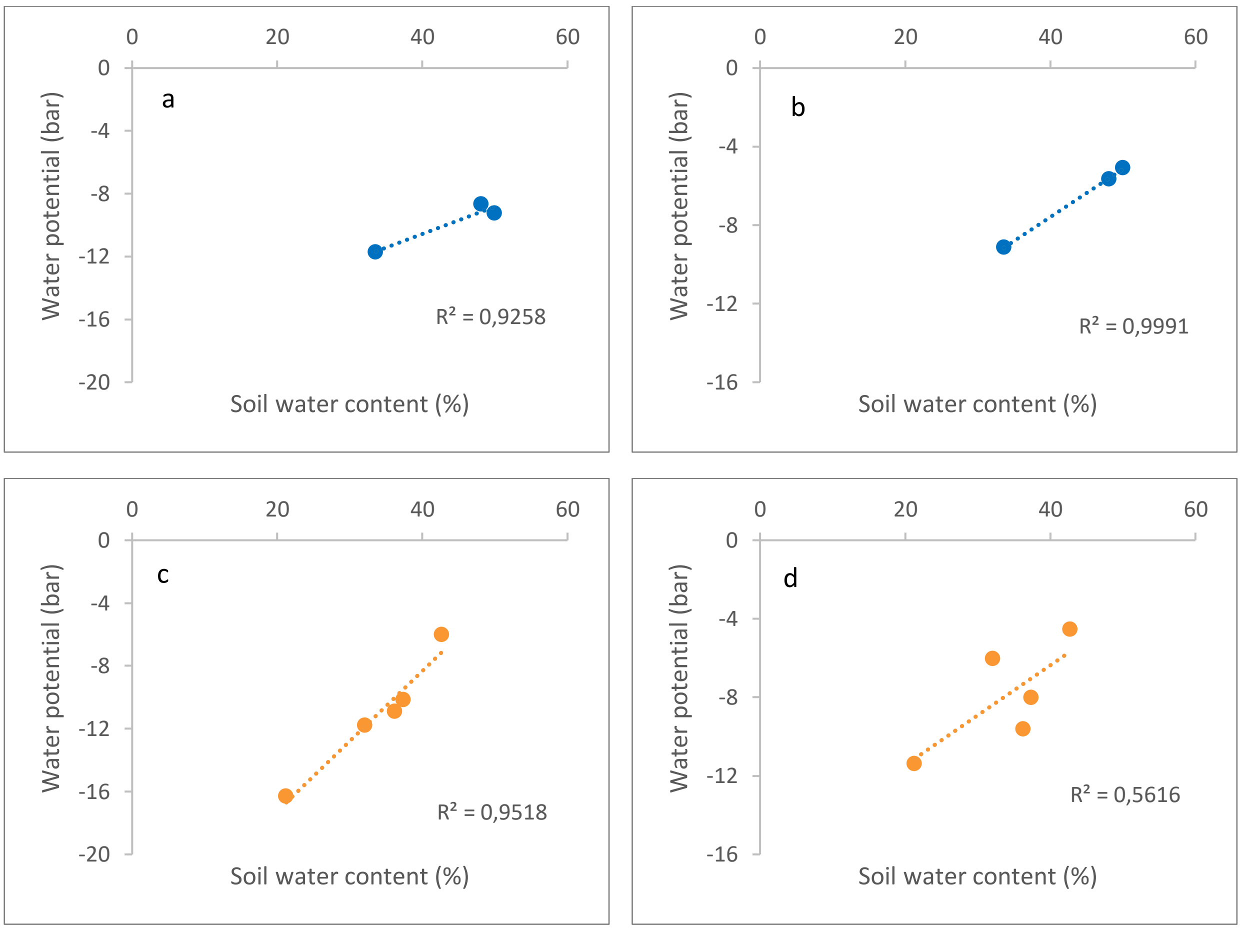

Figure 10 - Correlation between the soil water content and the plant water status for Agrostis capillaris in the a) A and in the c) D/E plots and Ranunculus acris in the b) A plots and in the d) D/E plots.

4 Discussion

The results suggest a significant correlation between the warmed soil temperature gradient, the weather, the soil water content, and the plant water status. Although this significant correlation is visible, it should be critically evaluated and analysed to deduct general implications for an ecosystem in the real world. This chapter will discuss the limitations and shortcomings of the research site. In combination with the limitations, the results will be interpreted with the help of existing literature on previous research. The interpretation of the results will be translated to the implications of these findings and what this means for the scope of this thesis topic. Finally, some recommendations will be discussed to possibly improve future research on this subject.

4.1 Limitations and methodology

The ForHot soil warming research locations are large in scale, not expensive, and easy to maintain. They are also present in an undisturbed ecosystem that simulates nature better than similar artificial setups. However, the research site is not perfect and entail some limitations. The soil warming is a natural phenomenon that also makes it uncontrollable. As mentioned in the results chapter, the warming in the warmer D and E plots was relatively higher compared to the MAT of previous years. This is because the MAT also includes the cold winter and autumn months. This results in the D and E plots then having a relative smaller overall warming difference compared to the colder plots because the cold air temperature cools the soil down. In addition to that, some of the D and E plots have also experienced more geothermal warming this year compared to other years which makes the WL of D and E even higher (P. Sigurðsson, personal communication, September 22, 2022). Analysing data from the D and E plots should be done with caution because of this. The warming levels are not uniform across all transects and the warming level is not a realistic scenario that climate can cause. However, it can be used to expose underlying ecological responses that might not be visible in weaker warming levels (Zhang et al., 2020).

The weather data was retrieved from a weather station 2,5 km away from the research site which leaves room for a lower validity. The Icelandic weather tends to change substantially over a short distance. That fact, in combination with the mountainous area around Hveragerði, allows for collected weather data to be different compared to the actual situation in the study area. Figure 5 shows that rainfall events can lead to a short decrease in the soil temperature in the warmer plots, however not every time. The distance between the study site and the weather station can possibly explain the irregular relationship between the rainfall and the lowering of the soil temperature.

The soil water content was measured weekly but ideally, more often would have been preferable to see the effect of individual rain events more precisely. When measuring the SWC, the plots were only measured once. With three similar transects, this should in theory mean three replicates which can justify this method.

For measuring the plant water status, a Scholander pressure chamber was used. This can be a proper method for assessing the plant water soil relation, but is a sensitive variable to measure, because the value changes quickly with the changes in the environment (Jones, 2006). In general, a pressure chamber for measuring plant water potential is mainly used for assessing irrigation needs in agriculture and improving crop production (Jones, 2006). This is often in warm, sunny, and stable climates during the measurement period which makes it more practical to use than in Icelandic conditions. A sudden cloud cover can influence the value of the PWS which will disturb the data collection and a rainfall event will prevent you from further collecting data that day. Examples like these and more made it challenging to collect the desired data, as concluded earlier by Ritchie & Hinckley (1975). This resulted in removing two measurement moments due to weather issues. The trees surrounding the study site also caused some difficulties, because the trees provided shade over some of the plots during parts of the day (Figure 1, plots 3C, 3D, 3E). The lack of sunlight changes the PWS which also led to leaving out some data. However, even when the protocol was executed well, the SD between the replicates on the same day was still quite high. 2,22 and 1,60 on average which makes the significant difference in PWS between A, D, and E plots small and uncertain. Using a pressure chamber has a high potential, for finding the relations discussed in this thesis. A study by Schwinning et al. (2005) used the pressure chamber in a similar way to measure predawn water potential in a natural ecosystem and had low SDs with clear relations between the variables. This study took place in a dry ecosystem and measured the predawn water potential which is less sensitive to fluctuations by the weather. These studies show that using a pressure chamber for plant water status measurements has the potential to be precise but must be used under the right circumstances with a suitable methodology.

4.2 Interpretations

When looking at the results with the limitations in mind, more precise conclusions can be made. In a broad sense, the results are in line with each other and are for the greater part supported by literature.

For the most part, the soil water content fluctuated moderately throughout the study period with few high and low peaks due to the stable and wet climate in Icelandic summers. It was correlated to the weather variables, air temperature, and rainfall. The warmer plots had a lower SWC than the colder plots. The plant water status for both plant species also fluctuated moderately throughout the study period for both plant species.

Although the number of observations can be considered low, it was enough to show that the correlation graphs with R^2 values (Figure 10) and the t-Tests showing the significance, that the PWS of Agrostis followed the SWC significantly and strong in the A and D/E plots. This was also the case for Ranunculus in the A plots but less in the D/E plots. The results suggest that the PWS decreases when the SWC decreases. It must be noted that there were only 3 observations in the A graphs which made it more likely to have a high correlation. These outcomes should be taken with caution. Although the correlation is strong, the actual change in the PWS is limited. The PWS for Ranunculus did not fluctuate very strongly and only for the last measurement moment, then Agrostis had a deviating dip. It must be noted, the values for the SWC and the PWS never reached a low critical level regarding water stress for the plant species (B.D. Sigurdsson, personal communication, July 17, 2022). The fact that potential water deficits in the study period did not lead to physiological changes in the plant such as the PWS is also supported by data about the stomatal conductance of the plant species. When Michielsen (2014) measured the stomatal conductance of Agrostis and Ranunculus, no significant stomatal closure caused by drought or a low SWC was observed across all the WLs.

A factor that should also be taken into account when assessing the correlation between the SWC and the PWS, is the thickness of the soil. The soil in GN is quite shallow (38,3 cm). Another ForHot research site is situated by the weather station 2,5 km away. This location is called GO (grassland old) and has the same setup as GN consisting of 5 transects with plots of different WLs. The soil in GO is 87,6 cm thick which is considerably more than GN (Sigurdsson et al., 2016). The thicker soil in GO is better capable of holding rain water at a 5 cm soil depth (Thetaprobe measurement depth). This is because the SWC was always higher in GO compared to GN (Annex 4). This shallow soil in GN can be a factor in ensuring a light form of a water deficit later in the study period which was starting to be visible in the plant water status data (Geroy et al., 2011b; Sigurdsson et al., 2016). The soil depth should therefore be considered when looking at similar experiments. A thicker soil might even diminish the effect of a rainfall deficit in combination with soil warming. A water balance analysis and a comparison with a thicker soil may be relevant when assessing the effects of geothermal warming.

As shown above, the previously mentioned variables are partially responsible for the pattern of the plant water status throughout the study period. Agrostis and Ranunculus are both plant species with different characteristics that also determine how the plant water status will evolve over time. A big and fundamental difference is that Agrostis capillaris is a monocot while Ranunculus acris is a dicot (Gargallo-Garriga et al., 2017). This means that the monocot Agrostis has a fibrous thin root system that tends to stay close to the surface. Ranunculus, a dicot, has a root system with a taproot. These roots are usually thicker and grow deeper into the soil. These characteristics make Ranunculus more resilient to soil warming and a soil with a lower water content. The root system enables Ranunculus to extract more water from the soil. It was also concluded by Michielsen (2014) that the stomatal conductance for Agrostis in GN was lower than Ranunculus. Stomatal conductance estimates the rate of H_2O and CO_2 gas exchange. It can be seen as a measure of sensitivity for water scarcity. The lower stomatal conductance of Agrostis means that there was less gas exchange. It tells us that Agrostis tends to preserve more water because it experienced more water shortage (Sellers et al., 1997; Dang & Cheng, 2004; Michielsen, 2014). These characteristics can be an explanation for why Agrostis correlated more with the SWC, the PWS, and the corresponding soil temperature than Ranunculus did (Figure 10).

4.3 Implications

The results with critical analysis of related literature have shown that the relationship and interactions found between the soil temperature, the weather, the soil water content, and the plant water status exist. It is however questionable to what extent this result is significant for the bigger picture of the changing climate and its effect on arctic ecosystems. The main issue of this thesis is that the changing plant water status was researched on plots with extreme soil warming (D/E plots, study period = +25,4°C, yearly average = +8,9°C). The relationship is present, but only weak and not to an extent where critical values of PWS or SWC were exceeded. This is still only the case when the soil is warmed to an intense level. Climate change will increase both air - and soil temperature (Soong et al., 2020), but not to the extent which was present in the D/E plots. It seems unlikely that the PWS of Agrostis and Ranunculus in arctic regions will change in any meaningful way when the climate will change like is predicted.

However, no serious rainfall deficits were measured during the study period to really test the response of the plant species. According to Sigurdsson et al. (2016), significant over-all drying of the surface layer is common in most years in the GN, especially in mid- to late summer when the water content of the unwarmed control plots was also reduced. When this is the case, a more significant change in the PWS can be the result. This makes the effect of soil warming on the PWS more substantial and thus relevant for the effects of climate change on ecosystems.

4.4 Recommendations

More detailed research on this topic can still add valuable insights on the effects of a changing climate on arctic ecosystems. The methodology for this research was suitable although not as elaborate and detailed as desired.

A more extensive methodology would add useful information. The water deficit in the soil was estimated based on the amount of rainfall, the soil temperature, and the soil water content. It would be valuable to assess the evapotranspiration to get a more complete insight into the water fluxes. This factor would demonstrate water stress better to see how the PWS changes in those circumstances. Another addition to this methodology would be to extend the study period over the full length of the growing season. As already noted, light droughts are more likely to occur in the later half of the growing season. These two options would provide a more detailed image of what happens in the ecosystem. Additionally, doing measurements in the B and C plots can also be interesting to see the effects of soil temperature, weather, and soil water content on warming levels which are more realistic for the temperature increase that climate change will cause in the future.

Time constraints limited the amount of data analysis that was possible although more in-depth research was possible. An example is the average soil temperature in the different plots. The predetermined plots with corresponding warming levels are not as stable as desired. The soil temperature, especially in the warmer plots, changes quite significantly each year which can make some plots have a different classification each year. This is shown by the large SD of this year's data (Figure 2). A reclassification before the analysis would reduce the variability of the results.

The last recommendation is doing some type of phenological data collection. This was planned to do and has been done with this thesis but in a way that was not random enough and would give a skewed representation of the situation in the study site. Therefore, it has been left out of the data analysis. Traits such as plant length, flower development, length of flowering, and leaf count could be interesting to study. This has also been done by Michielsen (2014) to study the effect of soil warming on plant length in combination with leaf stoichiometry, stomatal conductance, and the specific leaf area (SLA). This would increase the understanding of how plants' physiological appearance would react to changing water conditions for the plant.

These improvements to the research will give us more clear answers to what is happening in the ecosystem and thus what the consequences are on a larger scale.

5 Conclusion

It has shown that the warmed soil temperature gradient, the air temperature, the rainfall, the soil water content, and the plant water status are variables in the Icelandic grassland ecosystem which are connected. To answer the general research question of this research: How does a warmed soil temperature gradient, the weather and soil water content affect the plant water status of two common Icelandic grassland species Agrostis capillaris and Ranunculus acris? The air temperature partly determined the soil temperature. The soil temperature and the rainfall affected the soil water content in the soil. A higher soil temperature meant a lower soil water content and rainfall events increased the soil water content quickly. The soil water content is possibly one of the main drivers for the plant water status of Agrostis capillaris and Ranunculus acris. There was a significant difference between the plant water status for both Agrostis and Ranunculus when comparing the A plot values to the D/E plot values. For Agrostis PWS and SWC were strongly correlated in both the colder and warmer plots. This was also the case for Ranunculus but less strong in the warmer plots. Although the two variables correlated significantly, it did not result in critical changes in the plant water status. Based on the soil water content and the plant water status, no sign of water stress was measured in the plants. Agrostis seemed more sensitive to changes in the environment than Ranunculus.

This correlation with limited consequences does likely not form a major concern for arctic ecosystems. Agrostis capillaris and Ranunculus acris did not show reactions that will have important implications for other comparable ecosystems. Arctic ecosystems will stay vulnerable to future climate change and will show relatively strong changes. This was not the case for the arctic ForHot research site when it comes to PWS but possible changes in arctic ecosystems are important to understand, because it will eventually have an impact on the way we live on this earth. This is why it is still important to continue studying the consequences of changing circumstances on ecosystems.

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Appendix

Annex 1

This table shows the yearly average soil temperature in all the WLs in all the transects from the years 2020 and 2021. The last table shows the corresponding WL amounts.

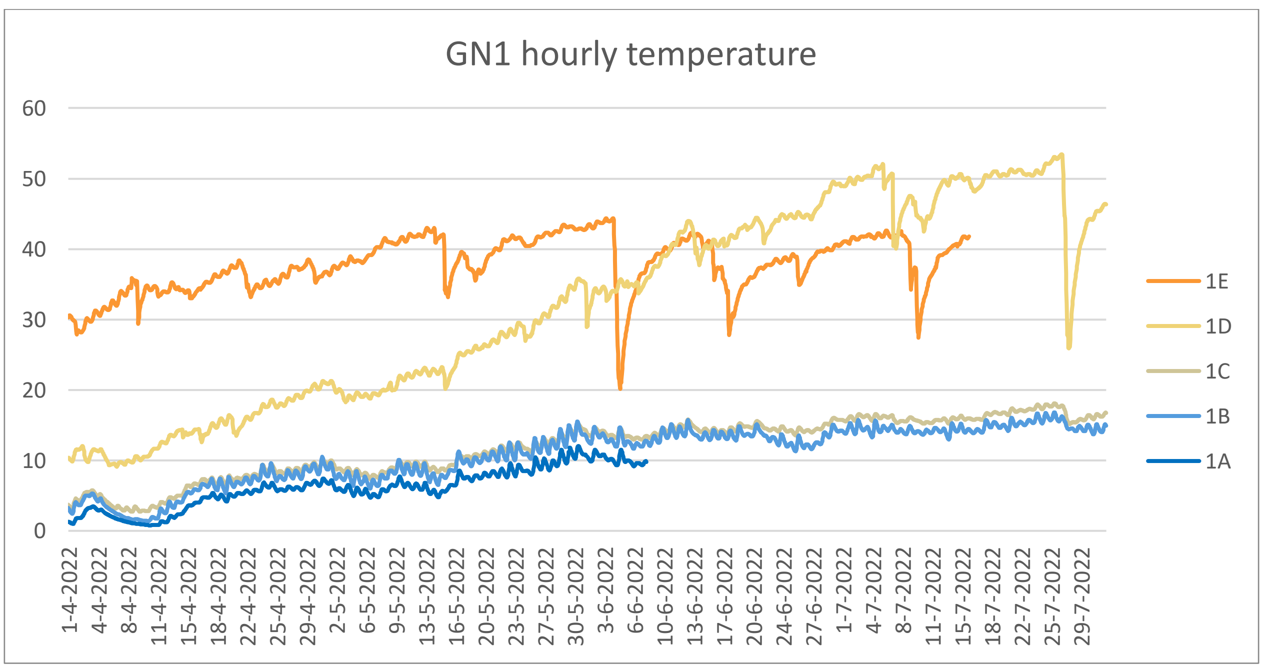
	1A	1B	1C	1D	1E	1F	2A	2B	2C	2D	2E	2F	3A	3B	3C	3D	3E	3F
2020	4,7	4,9	4,9	7,0	10,1	29,4	4,7	4,7	4,8	6,9	16,8	22,9	5,0	4,8	10,4	9,7	20,4	22,3
2021	4,8	5,0	5,6	8,3	19,0	40,7	5,0	5,1	5,5	8,0	18,0	24,1	4,9	5,1	15,0	14,3	25,2	32,0

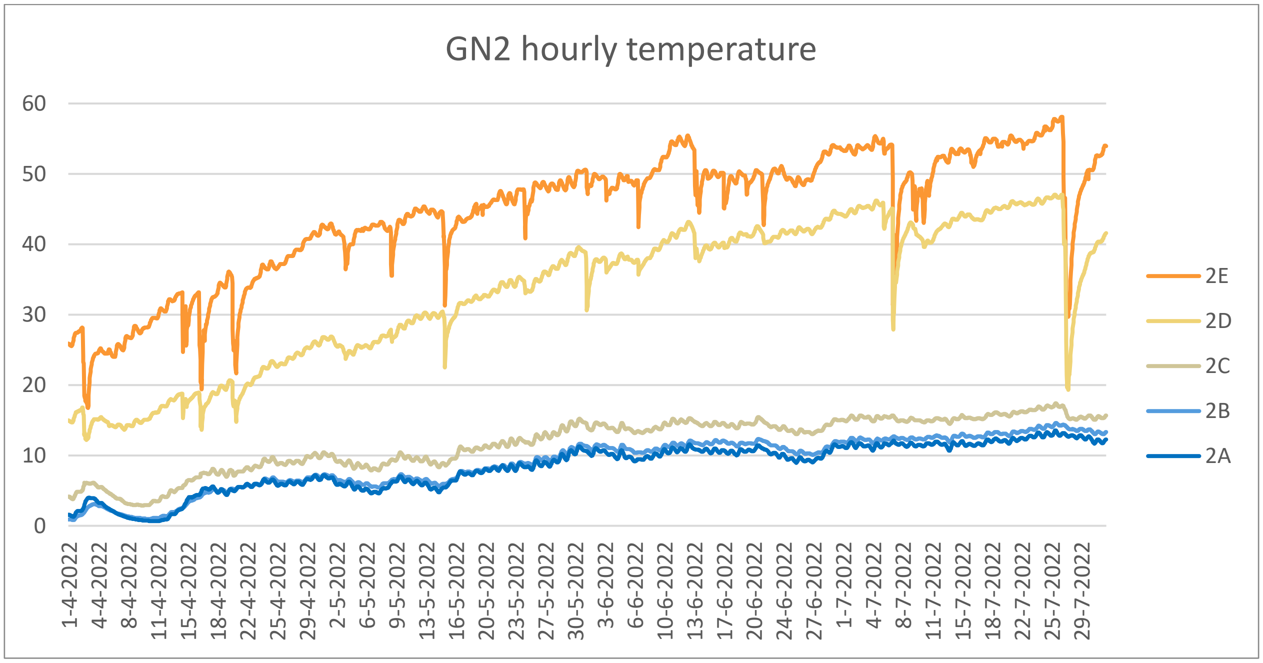
	A	B	C	D	E	F
2020	4,8	4,8	6,7	7,8	15,8	24,9
2021	4,9	5,1	8,7	10,2	20,8	32,3

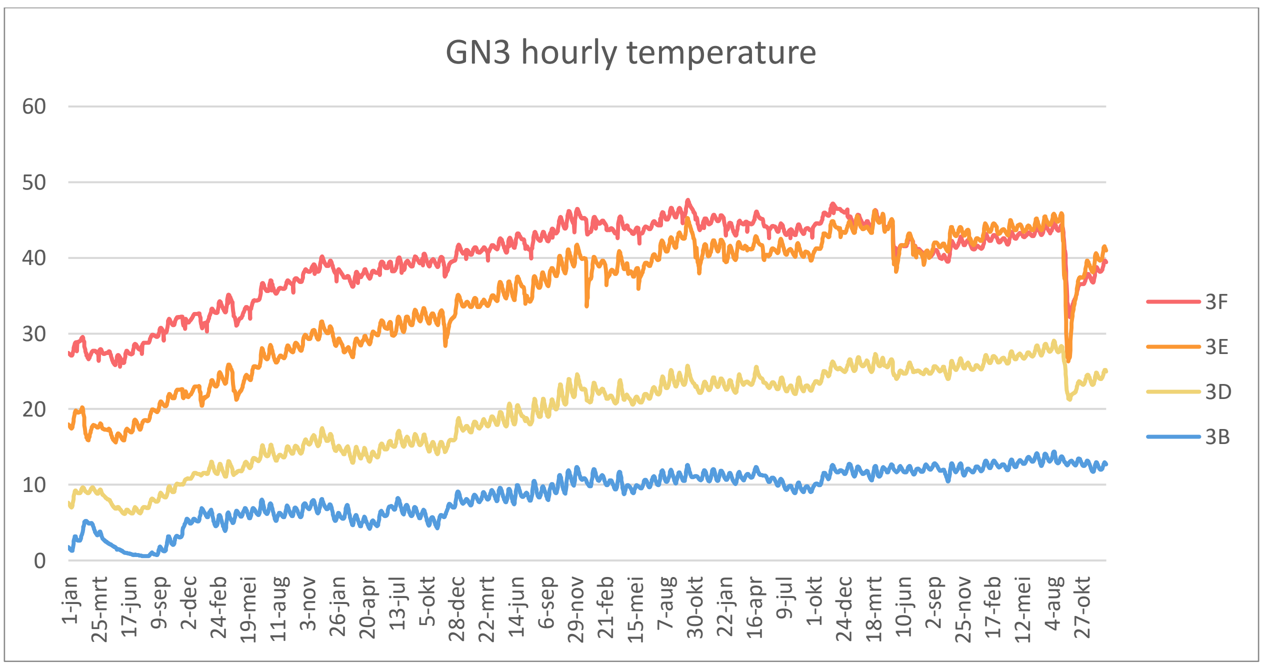
	WL					
2020	0	0,0	1,9	3,1	11,0	20,1
2021	0	0,2	3,8	5,3	15,8	27,4

Annex 2

These three graphs show the hourly temperature throughout the study period in the three separate transects. These graphs also show that some data is missing. The average temperature in the study period of each individual plot has been put into the table.







	A	B	C	D	E	F
1		10,8	11,8	32,1	37,9	
2	8,4	9,0	11,7	33,2	44,5	
3		8,8		19,3	34,8	39,8

Annex 3

Below are two tables with statistical two sample t-Tests assuming equal variances. A significance level of α=0,05 has been chosen. These tables show that there was no significant difference between the plant water status values in the D and the E plots.

Agrostis capillaris

Date	Plot	Mean (°C)	Variance (°C)	Observations	P-value P(T<=t)
7-5-2022	D	6,76	9,86	14	0,13
	E	5,28	3,21	15	
22-5-2022	D	10,47	4,47	15	0,34
	E	11,35	7,59	15	
1-6-2022	D	11,84	7,99	15	0,90
	E	11,72	7,56	15	
18-6-2022	D	9,84	1,14	7	0,14
	E	10,45	0,20	9	

Ranunculus acris

Date	Plot	Mean (°C)	Variance (°C)	Observations	P-value P(T<=t)
7-5-2022	D	4,33	2,50	15	0,43
	E	4,75	1,52	15	
22-5-2022	D	9,59	3,29	15	0,96
	E	9,63	5,67	15	
1-6-2022	D	5,74	1,99	15	0,28
	E	6,32	2,21	15	
18-6-2022	D	7,47	5,62	15	0,16
	E	8,57	3,26	15	

Below are two tables with statistical two sample t-Tests assuming equal variances. A significance level of α=0,05 has been chosen. These tables show that there was a significant difference between every plant water status value in the A plots compared to the D/E plots.

Agrostis capillaris

Date	Plot	Mean (°C)	Variance (°C)	Observations	P-value P(T<=t)
18-6-2022	A	9,24	1,98	15	0,03
	D/E	10,18	0,66	16	
4-7-2022	A	11,73	4,16	15	0,00
	D/E	16,29	10,13	15	

Ranunculus acris

Date	Plot	Mean (°C)	Variance (°C)	Observations	P-value P(T<=t)
18-6-2022	A	5,08	0,75	15	0,00
	D/E	8,02	4,60	30	
4-7-2022	A	9,14	3,45	15	0,00
	D/E	11,37	4,18	15	

Annex 4

The first Figure shows the change in soil water content in GO throughout the study period. The second graph shows the comparison between the total average soil water content in GN and GO of all the WL in all the transects.