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Higher temperatures increase nutrient availability in the High Arctic, causing elevated competitive pressure and a decline in *Papaver radicatum*



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Högre temperaturer förbättrar näringstillgängligheten i Högarkt, vilket ökar konkurrenstrycket och leder till en minskning av *Papaver radicum*

Bachelor degree thesis, 15 credits in *Physical Geography and Ecosystem Science*
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Bachelor thesis, 15 credits, in *Physical Geography and Ecosystem Science*

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Abstract

Linking changes in the vegetation cover with factors that can moderate the effects of climate change is central to our understanding of Arctic ecosystems and their susceptibility to change. The aim of this study has been to investigate the moderating effects of soil conditions. A High Arctic population of *Papaver radicatum* was studied in relation to the prevailing surface temperature, active layer depth, soil moisture and soil water variables such as pH and conductivity at the site.

Data was collected between 2004 and 2013 in the Zackenberg valley in NE Greenland. A negative trend over time was found in the number of *P. radicatum* flowers, as well as correlations between *P. radicatum* and conductivity, Ca^{2+} and dissolved total nitrogen (DTN). Surface temperatures increased, causing a deeper active layer and intensified weathering. The intensified weathering resulted in higher concentrations of ions in the soil water. No ion reached toxic levels, and the release of cations improved the nutrient status of the acidic soil. Together with warmer temperatures, this made the site more favourable for biological activity, elevating the competitive pressure. DTN decreased in correlation with dissolved organic carbon (DOC), since decomposition rates did not increase rapidly enough to meet the amplified demand on nitrogen and organic carbon. Due to *P. radicatum*'s high susceptibility to competition, the elevated competitive pressure is the most plausible reason for its decline.

Previous studies have found that *P. radicatum* responds to warmer temperatures with increased growth. The results of this study contradict those of the previous studies, which were performed with open top chambers or over an altitudinal gradient instead of over time. This stresses the importance of integrating the plants' full ecological context and allowing for complex feedback mechanisms to develop when studying the responses of Arctic plants to climate change.

Sammanfattning

Syftet med denna studie har varit att undersöka hur jordmånens egenskaper influerar arktisk växtlighet under en tid av globala temperaturförändringar. Vi behöver veta mer om hur olika faktorer kan påverka förhållandet mellan temperaturökningar och växtlighetens respons, då det ger oss en bättre förståelse för arktiska ekosystem och deras känslighet för förändringar. En högarktisk population av *Papaver radicatum* har studerats i relation till rådande ytemperatur, aktivt lager, jordfukt samt jordvattenvariabler såsom pH och konduktivitet.

Data samlades in mellan 2004 och 2013 i Zackenbergdalen, nordöstra Grönland. *P. radicatum* påvisade en negativ trend över tid samt korrelationer med konduktivitet, Ca^{2+} och totalt löst kväve (DTN). Ytemperaturerna steg, vilket ledde till ett djupare aktivt lager och ökad vittring. Med ökad vittring följde högre jonkoncentrationer i jordvattnet. Ingen jon nådde dock toxiska nivåer och ökningen av katjoner förbättrade näringstillgängligheten i jorden. Tillsammans med varmare ytemperaturer gjorde detta att platsen blev mer gynnsam för biologisk aktivitet, vilket sannolikt höjde konkurrenstrycket på platsen. DTN minskade i korrelation med löst organiskt kol (DOC), då nedbrytningstakten inte ökade tillräckligt fort för att täcka en förhöjd åtgång av kväve och organiskt kol. Då *P. radicatum* är mycket känslig för konkurrens är det ökade konkurrenstrycket den mest sannolika anledningen till dess nedgång.

Tidigare studier har funnit att *P. radicatum* reagerar på varmare temperaturer med ökad tillväxt. Resultaten i denna studie motsäger de tidigare studierna, som utfördes i kammarexperiment eller över en höjdgradient istället för över tid. Detta understryker vikten av att studera växterna i deras fulla ekologiska kontext samt att avsätta tid för att viktiga återkopplingsmekanismer ska hinna utvecklas.

Acknowledgements

First, I would like to thank my supervisor Lena Ström, who has put up with numerous report-length emails and my never-ending supply of questions. Thanks to her answering some of my questions already before the course started and helping me structure my work, my very optimistic time plan actually turned out to be somewhat manageable. I also want to thank Kirstine Skov at GeoBasis for providing much of the necessary data and answering many data-related questions.

As I am now soon heading back to Greenland before the course actually ends, some rearrangements of the presentation and opposition dates were necessary. I would like to direct a big thank you to everybody involved; course coordinator Jonas Ardö, opponent Verånika Trollblad, supervisor Lena Ström, examiner Margareta Johansson and respondent Souryana Nasser Al Din for making this possible and for being flexible with their time.

The used data come from GeoBasis and BioBasis, which constitute part of the Greenland Ecosystem Monitoring Programme. Data from GeoBasis were provided by the Department of BioScience, Aarhus University, Denmark in collaboration with Department of Geosciences and Natural Resource Management, Copenhagen University, Denmark. Data from BioBasis were provided by the Department of Bioscience, Aarhus University, Denmark in collaboration with Greenland Institute of Natural Resources, Nuuk, Greenland, and department of Biology, University of Copenhagen, Denmark.

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1. Introduction

Climate change is accelerated in the Arctic, causing the temperatures to rise 2-3 times faster than the global average (IPCC 2007). Arctic plant species are known to respond strongly to changes in the physical environment (Schmidt et al. 2012) and ecosystems in the region are already being severely altered by climate change (Post et al. 2009). Pearson et al. (2013) have projected that at least half of vegetated Arctic areas will shift to a different physiognomic class during this century.

Many uncertainties are linked to the role that Arctic vegetation will play in a changing climate. Arctic plant species respond to experimental warming with great heterogeneity (Elmendorf et al. 2012a), leading to effects that can both mediate and exacerbate climate change (McGuire et al. 2006; Wolf et al. 2008; Swann et al. 2010; Wramneby et al. 2010; Pearson et al. 2013). IPCC (2014) states that the vegetation changes will likely result in an overall positive feedback on the climate. With a high level of uncertainties and a risk for positive feedback mechanisms, it is important that we develop a better understanding of how Arctic plant communities respond to changes.

The great variety in how plants respond to experimental warming implies that other factors may be altering the effects of climate change. These factors include herbivory, soil nutrients and pH, precipitation, winter temperatures, snow cover and species composition and density (IPCC 2014). Linking changes in the vegetation cover with these factors is central to our understanding of the Arctic ecosystems and their susceptibility to change.

Papaver radicum is a ubiquitous species in NE Greenland (Bliss and Peterson 1992). Two previous studies have investigated the impacts of higher temperatures on *P. radicum*, finding an increase in the amount of flowers at higher temperatures (Molgaard and Christensen 1997) and concluding that moderate climate warming will likely promote the growth and establishment of the plant (Levesque et al. 1997). This study investigates the effects of surface temperature on a High Arctic population of *P. radicum*. It also includes soil conditions in the analyses, in an attempt to link the development in the *P. radicum* population to some of the abovementioned important moderators on climate change.

Inherent population stability but clear responses to changes in abiotic conditions make *P. radicum* suitable as a model species (Molau et al. 1996). *P. radicum* relies heavily on disturbances to decrease competition from other species, and studying how it reacts to changes in abiotic conditions can help us estimate how climate change will impact other disturbance-reliant species in the Arctic (Selin 2010).

The aim of this study is to investigate whether the development in a High Arctic population of *P. radicum* can be attributed to changes in surface temperature and soil conditions. Soil conditions include soil moisture, active layer depth and soil water variables such as ion concentrations and pH levels. To do this, a population of *P. radicum* in NE Greenland was monitored between 2004 and 2013 together with the prevailing soil and temperature conditions.

2. Background

2.1. *Papaver radicatum*

P. radicatum, or Arctic poppy, is native to Greenland and grows 10-30 cm tall, with hairy stems and leaves. The flower is normally big and yellow, but also white flowers occur. It flowers in June-July and is common in fell fields throughout Greenland (Gensbøl 2004). It is a perennial (Nilsson 1995) that is very tolerant to stress and that grows and reproduces over a wide range of environmental conditions (Levesque et al. 1997).

P. radicatum can be found in two types of populations, of which the first is situated in the mountains on alpine slopes, especially on rocks in loose scree or fissures. These are called primary populations. From here, snow and water can disperse seeds to sites at lower elevation, where secondary populations can be established on sand and gravel banks along rivers or on other low-lying disturbed areas (Knaben 1959; Nilsson and Nilsson 1986; Selin 2000). Consequently, individuals originating from the same primary population can be found both at high elevation on wind-exposed alpine slopes and in more favourable conditions at lower altitudes (Selin 2010). Secondary populations are from previous studies known to be relatively temporary (Nilsson and Nilsson 1986). This study focuses on a secondary population.

2.2. A changing Arctic

Future projections are uncertain (Oberbauer et al. 2013), but the Polar Regions are overall expected to keep experiencing an amplified climate change compared to other regions (Simon et al. 2005). A further increase in the growing season for plants is expected, with earlier snowmelt in the spring, later snow accumulation in the autumn or both (Maxwell 1992; Overpeck et al. 1997; Cleland et al. 2007; IPCC 2007).

Owing to the role that the Arctic plays in the global carbon cycle, climate change in the Arctic has received much research attention (Dorrepaal et al. 2009). Previous studies have showed that warming of the permafrost layer may trigger a feedback mechanism that can exacerbate climate change (Trumbore et al. 1996; Oechel et al. 2000; Dorrepaal et al. 2009; Schuur et al. 2009). In the Arctic, large storages of organic matter are held in the permafrost (Niklinska et al. 1999; Zimov et al. 2006; Ping et al. 2008; Tarnocai et al. 2009). As the temperatures get warmer, the decomposition increases. The increased flux of CO₂ to the atmosphere from large pools of soil carbon will further raise the CO₂ concentration, creating a positive feedback loop (Trumbore et al. 1996; Oechel et al. 2000; Dorrepaal et al. 2009; Schuur et al. 2009). Since the late 1970s, permafrost temperatures have increased with between 0.5°C and 2°C (IPCC 2014).

The ecological consequences of climate change in the Arctic are still poorly understood (Oberbauer et al. 2013). Phenological responses to longer growing seasons and higher temperatures have been observed via remote sensing, with indications of earlier green-up, greater greenness, longer green periods and reduced seasonality (Myneni et al. 1997; Jia et al. 2003; Xu et al. 2013). The plant species and growth forms that are driving these changes have however not been identified (Oberbauer et al. 2013). Ground-based

observations of individual plant species, like in this study, can aid our understanding of how the vegetation responds to climate change.

Trends in snow cover can complicate the relationship between temperature and plant productivity. In the beginning of the season, many sites are still covered by snow when the temperature reaches levels that are suitable for plant growth (Shaver and Kummerow 1992; Olsson et al. 2003). The timing of snow melt depends both on the depth of the snow cover and air temperatures, resulting in complex links between air temperature and productivity during the initiation of the season (Oberbauer et al. 2013). The timing of snowmelt can have consequences for plant productivity that linger throughout the season (Molgaard and Christensen 1997). Increased winter precipitation is expected as a consequence of climate change (IPCC 2014). If this results in later snowmelt, the growing season may be shortened or shifted into the early autumn, leading to a negative impact on plant productivity (Levesque et al. 1997).

2.3. High Arctic vegetation controls

The High Arctic, where the data was collected, has been described by Walker et al. (2005) as being composed of very low-stature vegetation, which mainly grows on mineral soils. Plants that grow in the High Arctic are subject to a greater selective pressure for temperature sensitivity than plants in the Low Arctic and alpine zones, as plants in the High Arctic must be able to grow in the lowest temperatures and shortest growing season (Billings 1987). Studies have shown that temperature increases lead to a greater response in plants in the High Arctic than in any other climate zone, with a greater proportional increase in growing season (Arft et al. 1999). The High Arctic plants will consequently both experience the greatest warming due to climate change and have the most pronounced responses.

As tundra ecosystems are strongly nutrient limited, warmer temperatures alone will not yield higher productivity rates. Warmer growing seasons will likely increase rates of decomposition and mineralization (Chapin and Korner 1996), but increased soil temperature may result in nutrient immobilization by soil microorganisms (Henry and Molau 1997). Additionally, Gehrke et al. (1995) found that higher levels of UV-B radiation in high latitudes reduce populations of decomposing organisms. These two factors lead to lower litter quality, which could act as a negative feedback mechanism since it reduces nutrient availability (Henry and Molau 1997).

2.4. Arctic biodiversity

During the past few decades, dramatic shifts in vegetation composition, diversity and biomass in numerous Arctic tundra sites have been observed (Grabherr et al. 1994; van Wijk et al. 2004; Tape et al. 2006; Hudson and Henry 2009; Post et al. 2009; Callaghan et al. 2011b; Hill and Henry 2011). Elmendorf et al. (2012a) synthesized the results from 61 worldwide tundra studies of experimental warming, which had been conducted during a period of up to 20 years. The synthesis showed an overall decrease in species diversity and evenness, a decrease in moss and lichens cover and an increased growth of deciduous shrubs and graminoids (Elmendorf et al. 2012a).

Over the last 20 years, shrubs have generally expanded their ranges and/or growth in the Arctic (Hudson and Henry 2009; Callaghan et al. 2011a; Callaghan et al. 2011b; Hill and Henry 2011; Myers-Smith et al. 2011; Elmendorf et al. 2012a; Elmendorf et al. 2012b). This is an example of a shift in species composition and in the balance between functional groups, as a consequence of altered inter-specific competition between plant species (Myers-Smith et al. 2011). In Greenland, early invasion of a fell field community by low shrubs has been observed (Callaghan et al. 2011a). Generally, tundra plant biodiversity is threatened by changing dominance of existing species, changed abiotic conditions and the invasion of species from lower latitudes (Billings and Peterson 1992; Chapin and Korner 1996).

2.5. Vegetation can both mediate and exacerbate climate change

With warmer temperatures and an elevated level of CO₂ in the atmosphere, the rate of Arctic vegetation productivity has been predicted to rise (Schlesinger and Bernhardt 2013). Several studies have attempted to estimate the effects that an increased vegetation cover can have in the Arctic. Among these effects are negative feedbacks of CO₂ sequestration and increased evapotranspiration, as well as the positive feedback of decreased albedo (Wolf et al. 2008; Swann et al. 2010; Wramneby et al. 2010; Pearson et al. 2013). Also energy partitioning as well as the exchange of other greenhouse gases may be altered (McGuire et al. 2006). The net effect of future warming is largely dependent on whether the increases in plant productivity can offset warming-induced increases in soil respiration (Euskirchen et al. 2009) and the methanogenesis in thawing permafrost (McGuire et al. 2009). According to IPCC (2014), the net effect will likely be an overall positive feedback on the climate.

Except for being able to mediate or exacerbate climate change, plant composition also has a direct impact on active layer depth, forage quantity and quality, nitrogen cycling, productivity and decomposition, snow distribution and albedo (Chapin et al. 1996; Sturm et al. 2001; Cornelissen et al. 2007; Blok et al. 2010). This means that an altered plant composition can produce feedback mechanisms that bounce back on the plant community itself. It can therefore take time for the long-term consequences to develop.

3. Site description and methods

This section starts with a short site description and then moves on to briefly describing the different sampling methods, materials, data handling and the statistical analyses. A more extensive description of the methods of the soil water sampling and the monitoring of the active layer depth, surface temperature and soil moisture can be found in Sigsgaard et al. (2014). More in-depth information on the counting method of *P. radicum* is available in Schmidt et al. (2014).

3.1. Site descriptions

The variables have been sampled from two adjacent sites, which are located at a High Arctic research facility in the Zackenberg valley in NE Greenland. In Figure 1, an overview of the valley can be seen, with a red ring marking the location of the two sites. The sites are situated about 10 m from each other, at 35 m.a.s.l. (Sigsgaard et al. 2014). The first site is called Mix 1 and can be found at UTM 27N 8264348 mN, 513567 mE. At Mix 1, soil water, active layer depth, surface temperature and soil moisture have been sampled (Sigsgaard et al. 2004). The second site is called Papaver 3 and can be found at UTM 27N 8264353 mN, 513575 mE. Papaver 3 is the site where *Papaver radicum* has been counted (Schmidt et al. 2014).

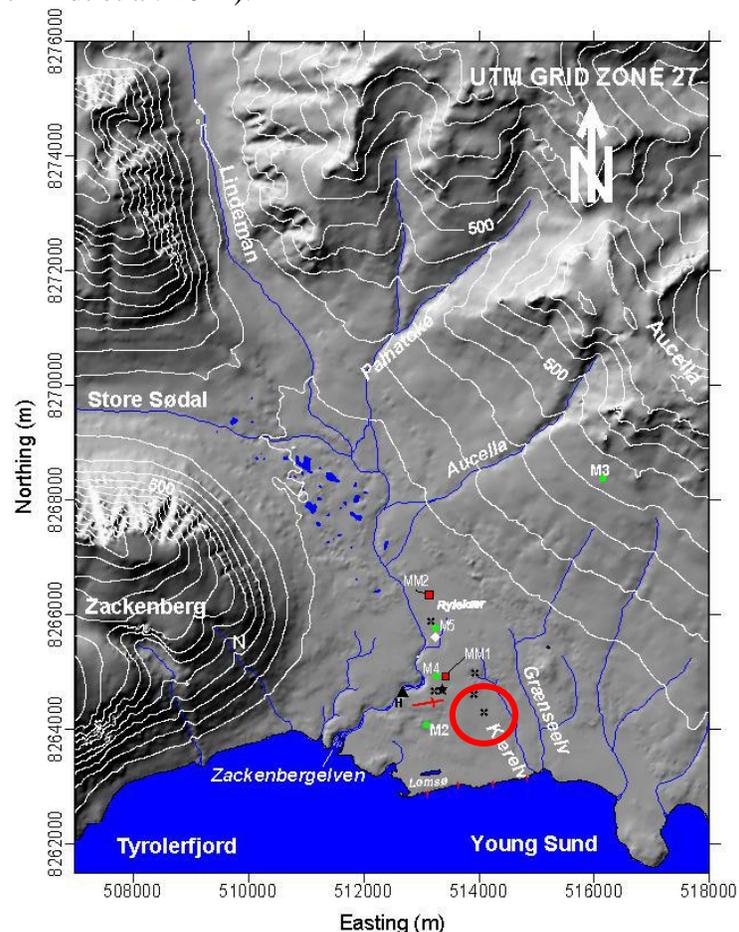


Figure 1. The Zackenberg valley, with a red circle marking the location of the two sites that were used in this study. Map included with permission from Sigsgaard et al. (2014).

Mix 1 is covered by mixed heath vegetation that grows on a well-drained, coarse and sandy soil (Sigsgaard et al. 2014). The sampling at Mix 1 is done by GeoBasis, which is operated by Department of Bioscience, Aarhus University, in collaboration with Department of Geosciences and Natural Resource Management, University of Copenhagen (Rask Mylius et al. 2014). GeoBasis is one of five subprograms in the Greenland Ecosystem Monitoring (GEM) research programme. The GEM programme monitors ecosystems and climate change effects and feedbacks in the Arctic. The programme has been active in Zackenberg since 1995 (GEM n.d.; Hviid n.d.). In Figure 2, a photo of the site can be seen. Soil water was sampled under the stones that the red arrows in Figure 2 point toward. In this study, only soil water data from 5 cm depth was used. Soil moisture and surface temperature were measured with equipment in the box and the active layer depth was measured just outside the box. See detailed descriptions in part 3.2. and 3.3.

Figure 3 shows a photo from the end of July 2015. This photo can be compared to the photo in Figure 2 in order to judge the changes in vegetation cover that have occurred on the site between 2005 and 2015. It can thus also be useful when estimating the changes that occurred between 2004 and 2013.

Papaver 3, the plot where the *P. radicum* flowers were counted, is monitored by the BioBasis programme, which is operated by Department of Bioscience, Aarhus University (Rask Mylius et al. 2014). BioBasis, like GeoBasis, is one of the five subprograms in GEM (Hviid n.d.). Papaver 3 is 9x10 m large and is divided into four subplots (Schmidt et al. 2014).



Figure 2. Mix 1, the site where soil water, active layer depth, soil moisture and surface temperature were sampled. Photo used with permission from Sigsgaard et al. (2014).



Figure 3. This photo from 2015 shows the vegetation cover ten years after the photo in Figure 2.

In Figure 4, another photo from 2015 can be seen, showing Mix 1 in the foreground and the southwest subplot of Papaver 3 in the background. This photo was taken after the period of interest (2004-2013) had ended, but serves to visualize how the sites are located in relation to one another. Mix 1 is situated adjacently to Papaver 3, on the west side.



Figure 4. Within the red circles are the poles that mark the southwest subplot of Papaver 3. Mix 1 is situated just west of Papaver 3.

3.2. Soil water

The monitored soil water variables and their abbreviations can be seen in Table 1. In the remainder of this thesis, the abbreviations will be used. As previously mentioned, only soil water data from 5 cm depth was included in the analyses.

The soil water collection bottles were kept under stones in order to protect the bottles from sunlight and to protect the cables from foxes (Fig. 2) (Sigsgaard et al. 2014). For soil water to be collected, it first needed to pass into a suction cup lysimeter, which was located at a depth of 5 cm in the soil. The suction cup has a pore size of 2 microns and can be seen in Figure 5. In this study, a model called *Prenarts Superquartz* was used. It is made of porous PTFE (Teflon) and quartz and is most applicable for studies on soil

Table 1. Monitored variables and abbreviations.

| | Abbreviation |
|---------------------------------|-------------------------------|
| pH | |
| Conductivity | |
| Alkalinity | |
| Chloride | Cl ⁻ |
| Nitrate | NO ₃ ⁻ |
| Sulfate | SO ₄ ²⁻ |
| Calcium | Ca ²⁺ |
| Magnesium | Mg ²⁺ |
| Potassium | K ⁺ |
| Sodium | Na ⁺ |
| Iron | Fe ²⁺ |
| Aluminum | Al ³⁺ |
| Manganese | Mn ²⁺ |
| Ammonia | NH ⁴⁺ -N |
| Dissolved total nitrogen | DTN |
| Dissolved organic carbon | DOC |

nutrient status. A Teflon tube, which can be seen in Figure 6, connects the probe to the soil surface and to the collection bottle. The collecting bottle can hold 1000 ml and has a screw cap with a small, sealable outlet. To cause soil water to pass from the suction cup lysimeter to the collection bottle, a handheld vacuum pump was used on the bottle's sealable outlet to create a negative pressure in the bottle. Figure 7 illustrates this procedure. Around 0.3-0.4 atm was applied on the bottle with a daily frequency during the season. The negative pressure caused soil water to flow upward in the Teflon tube and into the collection bottle (Sigsgaard et al. 2014).

Figure 5. The suction cup lysimeter. Photo used with permission from Sigsgaard et al. (2014).



Figure 6. An example of what the installation can look like. Photo not from Zackenberg, used with permission from Sigsgaard et al. (2014).

The first few ml of water from each season were used to clean the bottle and then discarded. If there was not enough soil water in the bottle after a day, more negative pressure was applied. Date and time of start and collection were recorded, as well as the date and time when additional negative pressure was put on the bottle. When at least 80-100 ml had been collected, it was brought to the Zackenberg station. The soil water variables were then analysed at three different locations. pH, conductivity and alkalinity were analysed at the Zackenberg research station. The analyses of all ions except ammonia were performed at the Department of Geoscience and Natural Resource Management at University of Copenhagen. DOC, ammonia and DTN were analysed at the Department of Biology at University of Copenhagen (Sigsgaard et al. 2014).



Figure 7. The negative pressure in the collection bottle was created with a vacuum pump. Photo used with permission from Sigsgaard et al. (2014).

The frequency of the soil water sampling differed considerably from year to year, depending on how dry the individual years were. During dry years, less soil solution could be extracted. Samples were normally taken from June to September, whenever the soil conditions allowed. In this study, only samples from July and August were included.

3.3. Active layer depth, surface temperature and soil moisture

Active layer depth was measured with a metal probe on the downstream side of the box in Figure 2. Since the probe was inserted on the downstream side, the measurements did not disturb the soil water or the soil moisture sensors. Care has been taken to use the same hole during the season, to minimize the risk that stones in the soil would be in the way when the active layer was measured. Active layer depth was measured with a frequency of 2-7 days, at the same time as soil moisture (Sigsgaard et al. 2014).

A TinyTag logger recorded the surface temperatures once per hour throughout the year. Also temperatures at 10 and 30 cm depth were monitored at this location. In this study, only analysed surface temperature data has been used. The TinyTag loggers were located in a waterproof box that can be seen in Figure 8. The TinyTag loggers are the small yellow boxes. (Sigsgaard et al. 2014).

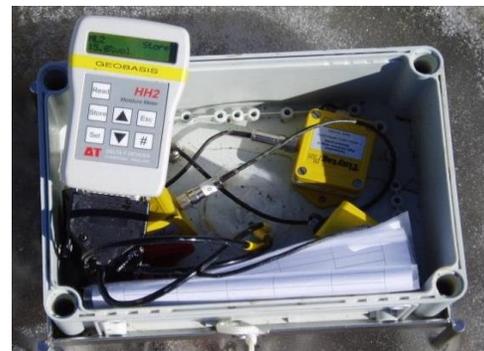


Figure 8. The HH2-meter to the left and the TinyTag loggers to the right are used for measuring soil moisture and surface temperature respectively. Photo with permission from

Soil moisture was measured with an HH2-meter, which can be seen in the left part of Figure 8. A soil sensor was installed at 5 cm depth upstream from the plot and was once a week connected to the HH2-meter via a ThetaProbe. This study has only used soil moisture data from 5 cm depth, but there is also data for 10 cm depth. Soil moisture was measured every 2-8 days, at the same time as active layer depth (Sigsgaard et al. 2014).



Figure 9. *Papaver radicum* was counted once per year.

3.4. *Papaver radicum*

The total amount of *P. radicum* flowers in Papaver 3 has been counted once per year, in mid-July or early August when all or most flower buds have opened. All four sections of the plot were counted on the same day. The total count includes buds, flowers and senescent flowers. When counting, pieces of chord totalling 100 m, tally counters and a notebook or a Dictaphone were used. One chord was tightened around each section of the plot. The chords were then moved one at a time, a process that was repeated until the entire plot had been covered. The results were dictated to the Dictaphone or written in the notebook for at least every

100 recordings (Schmidt et al. 2014). *P. radicum* can be seen in Figure 9.

3.5. Data handling

The data has either been provided by Kirstine Skov, academic employee at Geosciences and Natural Resource Management, University of Copenhagen (Department of Geosciences and Natural Resource Management n.d.) or accessed through the Greenland Ecosystem Monitoring (GEM) database. Kirstine Skov has the main responsibility for the field season and data validation in the GeoBasis Zackenberg programme. The GEM database makes data from the subprograms available free of charge on <http://data.g-em.dk>. The GeoBasis data have been collected by the Department of Bioscience, Aarhus University, in collaboration with the Department of Geosciences and Natural Resource Management, University of Copenhagen. The BioBasis data were collected by the Department of Bioscience, Aarhus University, in collaboration with Greenland Institute of Natural Resources, Nuuk, and Department of Biology, University of Copenhagen (GEM n.d.).

This study focuses on the interannual variability during the years 2004-2013. In order for the years to be comparable, the same time period was used for all years. The time period was limited to July and August, as the peak of the growing season was of most interest.

Kirstine Skov, GeoBasis, provided soil water data. The data includes the results from 1-5 soil water analyses from each year, depending on the amount of soil water that was extracted. 2009 was a particularly dry year and soil water could only be extracted once. For all other years, soil water was extracted at least twice. At a few occasions, the extracted soil water was only enough for some analyses but not for others. This means that some variables have a larger sample size than others and that some years hold three values for certain soil water variables but only one value for other variables. The sample size consequently varies between the different soil water variables.

Soil water averages were calculated for each individual year, and these averages were later used in the statistical analysis. When soil water had been extracted just once in a year, the single value was used instead of an average. During some years, the sample distribution was skewed, with soil water being extracted twice in August and not at all in July. To compensate for this, the averages of other variables have been adjusted to fit the soil water sample distributions of the individual years. More about this can be found in the following paragraphs. Due to insufficient sample sizes, the ions NO_3^- , Fe^{2+} , Al^{3+} and Mn^{2+} were not included in the data analysis. Two outliers were removed from Cl^- in 2012 and one from DOC in 2013.

Kirstine Skov, GeoBasis, provided data also on the active layer depth. The data was validated from the principle that active layer in July and August does not decrease over the season. For the data analysis of active layer, a within-season maximum value and averages for July and August were computed. Due to varying lengths of the active layer sampling seasons, a fixed date for the maximum value was used, in order to be able to include also the years with a shorter sampling season. The fixed date was set to the 28th

of August. Values for this date were interpolated or extrapolated from the values that were closest in time.

Average active layer depth was tested against soil water variables and soil moisture. When tested against soil water variables, the active layer depth averages were based on values that had been interpolated and extrapolated to adhere to the same dates that the soil water was sampled on. This was done by fitting a linear equation to the existing active layer measurements of a given year, calculating day of the year (DOY) for the wanted dates and then inserting the DOY in the equation. Thus, for a year with three soil water samples, the average active layer depth was based on estimated active layer depths on the very dates that the three soil water samples had been taken on. As the sampling size varies between soil water variables, different active layer depth averages have been used for different soil water variables. When active layer depth was tested against soil moisture, all active layer depth measurements from July and August were included in the yearly average. This was possible since the active layer depth was measured on the same dates as soil moisture.

Data for surface temperature was downloaded from the GEM database and averages were computed from the hourly measurements. The time period was adapted to the sampling dates of the variables that surface temperature was tested against. When tested against soil water variables, the average was calculated from 00:00 on the day of the first soil water sample until 23:00 on the day of the last soil water sample. In this way, an attempt has been made to compensate for temporal skewedness in the soil water sampling. In 2004, the measurements did not start until the evening of the 5th of July and then, the average includes values from 00:00 on the 6th of July. The measurements end on the 12th of July 2013 and for that year, the average includes values up to 23:00 on the 11th of July. When there was only one soil water sample during a given year, only that day and night was used when calculating the average. When testing surface temperature against soil moisture and *P. radicum*, a temperature average of the whole of July and August was used for each year.

Soil moisture data was downloaded from the GEM database and values were averaged for July and August. Soil moisture and soil water variables were not tested against each other, since they are not sampled on the same date and cannot be interpolated. The soil moisture averages were tested against active layer depth, which has been measured on the same dates, against July and August averages for surface temperature and against the yearly total count of *P. radicum*.

Data for *P. radicum* was downloaded from the GEM database. The total counts for the four subplots that make up Papaver 3 were summed, so that the new values represent the whole plot. The total count states the total amount of flower buds, flowers and senescent flowers in mid or late season, a number that reflects the conditions of the given year. Data on grazed flowers shows that only very few flowers (maximum 3 per year) were grazed during July and August 2004-2013 and therefore, grazing has not been taken into account.

3.6. Statistical analysis

The statistical analysis was carried out in R, version 3.2.4, a programming language and an open source software environment for statistical computing and graphics. It was downloaded on the 20th of February 2016 from <https://cran.r-project.org>. Two kinds of statistical tests have been used in this study; linear regression and correlation. Regressions were used to identify trends over time and to find dependencies on surface temperature, active layer depth and soil moisture. Correlations were used to identify covariance between two variables over time. The data was graphed to see whether any variables would benefit from being transformed to a logarithmic or exponential scale for a better fit. No such cases were found and thus, no data has been transformed.

The following linear regressions were performed:

- All variables against time
- *P. radicum* against surface temperature
- *P. radicum* against average active layer depth
- *P. radicum* against within-season maximum active layer depth
- *P. radicum* against soil moisture
- Soil water variables against surface temperature
- Soil water variables against average active layer depth
- Soil moisture against surface temperature
- Average active layer depth against soil moisture

Correlations tests were performed on all soil water variables and between the soil water variables and *P. radicum*. Active layer depth was used both as a response variable and as an explanatory variable, as it can be assumed to be dependent on ambient parameters such as temperature, but may work as an explanatory variable for soil water variables.

Standard deviations have been computed for all variables except for *P. radicum*, as *P. radicum* is based on just one counting per year. The standard deviations of the soil water variables have not been included in the graphs but are instead presented in the end of the results section. Since the yearly soil water averages are based on a varying number of samples, a higher standard deviation may not mean that the variability during that year has been higher, but could just be a consequence of a larger sample size. Similarly, a lower standard deviation does not necessarily mean that there was less variation during the season, but may be caused by a very low sampling number. Therefore it has been considered that displaying the standard deviations of the soil water variables in the graphs could be misleading.

4. Results

The results section is divided into four parts, where trends over time, dependencies on surface temperature, correlations between the variables and an overview of the standard deviations of the soil water variables will be presented in due order. In the end of each of the first three parts, more detailed statistics are displayed in a table.

4.1. Trends over time

This part presents the statistically significant trends that have been identified when all variables were run against the years 2004-2013 in linear regressions. During the given time period, there was a negative trend in the number of *P. radicum* flowers at the site (Fig. 10). The trend is statistically significant ($p = 0.022$). With an adjusted r^2 of 0.44, 44% of the trend can be explained by the equation in Figure 10. On average, there were 15.6 fewer flowers each year.

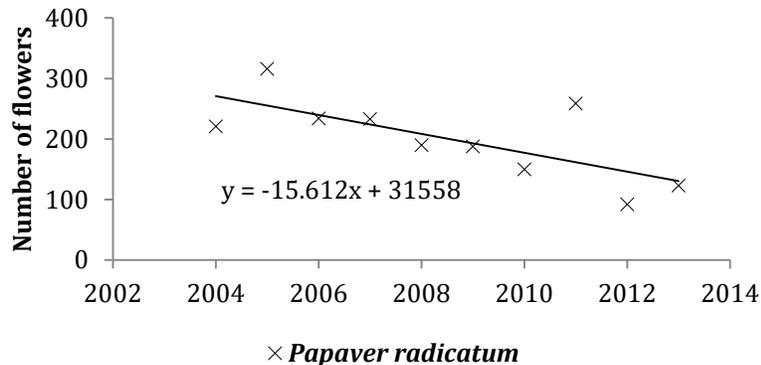


Figure 10. The trend over time in the yearly maximum number of flowers in a High Arctic secondary population of *Papaver radicum* at a lowland site in NE Greenland.

A positive trend in conductivity was found (Fig. 11). With an equation that is almost exactly the inverse of that of *P. radicum*, the positive trend in conductivity mirrors the negative trend in *P. radicum*. 66 % of the increase in conductivity can be explained by the equation displayed in Figure 11, given its adjusted r^2 of 0.66. Also this trend is statistically significant ($p = 0.005$).

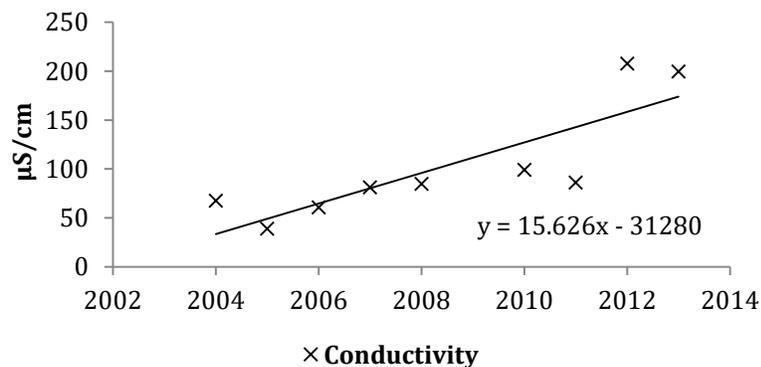


Figure 11. The development over time in the average July and August conductivity of the soil solution. Soil water samples were extracted from a site adjacent to the counting area of *P. radicum*.

Trends in ion concentrations in the soil solution are visualized in Figure 12 and 13. For better interpretability, Ca^{2+} and Cl^- are presented in Figure 13 with a scale of 0-60 ppm, whereas Mg^{2+} and K^+ are presented in Figure 13 with a scale of 0-7 ppm. With p-values at <0.01 and adjusted r^2 at >0.60 , the four ions show statistically highly significant trends with a good fit to the line. In Figure 12 and 13, a higher rate of increase can be noted for Cl^- and Mg^{2+} than for Ca^{2+} and K^+ . Ions that have been sampled but that show no statistical trend are the cations NH_4^+ and Na^+ as well as the anion SO_4^{2-} .

In Figure 12, the positive trends in the concentrations of the cation Ca^{2+} and the anion Cl^- can be seen. A particularly significant trend can be seen in in Figure 12b, where the trend in Cl^- has a p-value of <0.001 and an adjusted r^2 of 0.84.

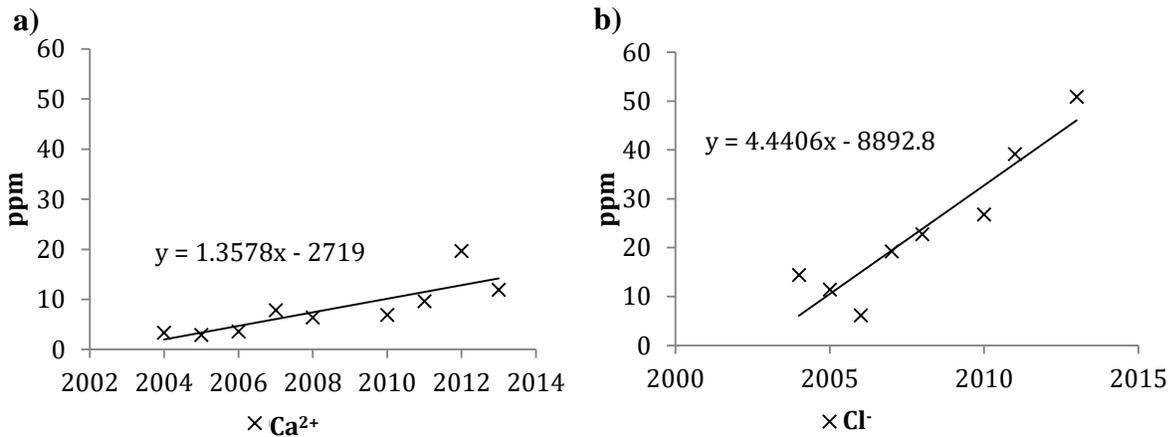


Figure 12. Trends in average July and August ion concentrations in the soil solution over time at a lowland site in NE Greenland. The ions are presented at a scale of 0-60 ppm, with panel a) showing the positive trend in Ca^{2+} and panel b) showing the positive trend in Cl^- .

Figure 13 shows the positive trends of the cations K^+ and Mg^{2+} . These trends are similar to the trends of Ca^{2+} and Cl^- respectively, but have occurred at much lower concentrations.

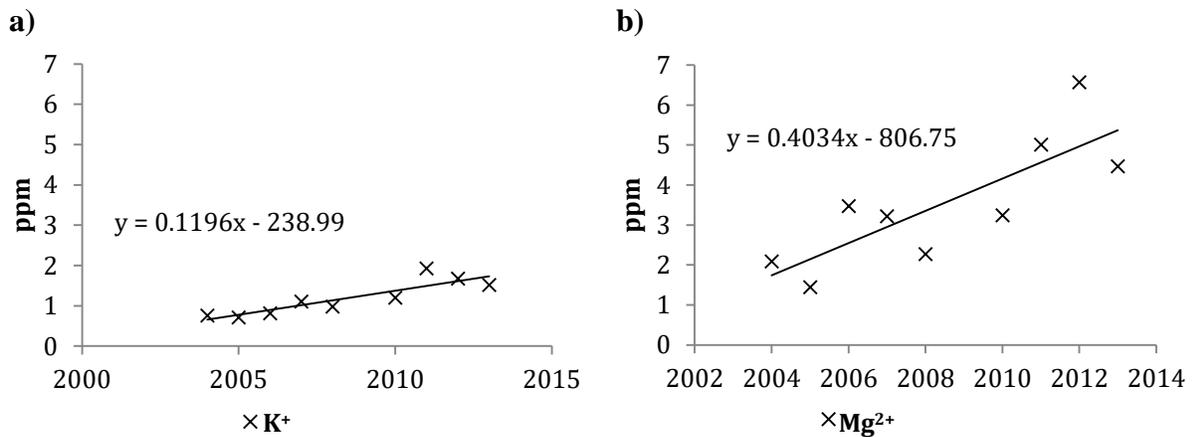


Figure 13. Trends in average July and August ion concentrations in the soil solution over time at a lowland site in NE Greenland, at a scale of 0-7 ppm. Panel a) shows the positive trend in K^+ and panel b) shows the positive trend in Mg^{2+} .

A negative trend in DTN was found (Fig. 14). With a p-value of <0.001 and an adjusted r^2 of 0.73, only CI⁻ has a statistically more significant trend. 73% of the trend can be explained by the equation in Figure 14.

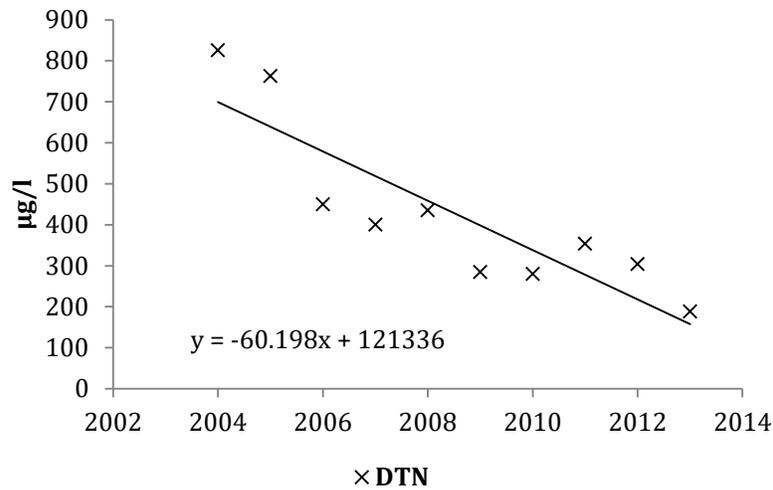


Figure 14. The trend over time for the July and August average of dissolved total nitrogen (DTN) in the soil solution at a lowland site in NE Greenland.

A negative trend in soil moisture and a positive trend in surface temperature were found (Fig. 15). These are the statistically least significant trends over time, with p-values of 0.034 and 0.042 respectively. The adjusted r^2 are 0.38 and 0.35, meaning that a relatively low fraction of the observations fit to the line of regression. The average summer soil moisture at 5 cm depth shows a negative trend that corresponds to about 10 percentiles between 2004 and 2013, whereas the average surface temperature in July and August shows a positive trend that corresponds to about 1°C during the same time period (Fig. 15). There is a high interannual variability in the standard deviation for soil moisture, whereas the standard deviation is more consistently high for surface temperature.

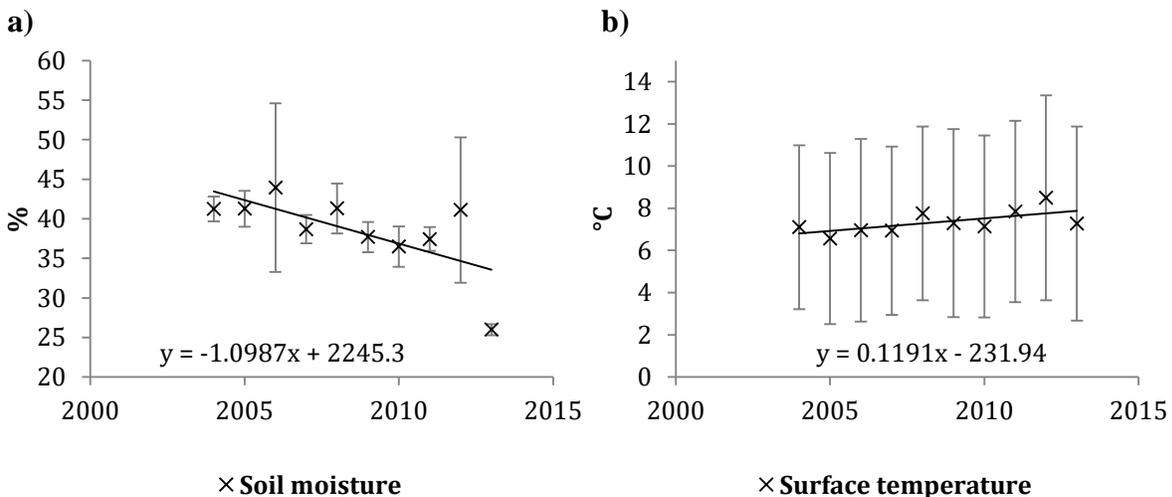


Figure 15. The trends in average July and August soil moisture (panel a) and surface temperature (panel b), with standard deviations. These variables were measured at a lowland site in NE Greenland, on the same site as the collection of the soil water.

In Table 2 follows a more detailed list of the statistics. As can be seen, Cl⁻ has the most statistically significant trend. It does however also have the smallest sample size and thus the lowest d.f., as it lacks data from 2009 and 2012. DTN has both a large sample size, a good fit to the line and a low p-value. A target significance level of 0.05 was used for the critical values.

Table 2. More detailed statistics for the trends over time.

| | p-value | Adjusted r² | F-statistic | d.f. | Critical value |
|----------------------------|----------------|-------------------------------|--------------------|-------------|-----------------------|
| <i>Papaver radicum</i> | 0.02158 | 0.4412 | 8.105 | 8 | 5.32 |
| Conductivity | 0.004784 | 0.6598 | 16.52 | 8 | 5.32 |
| Ca²⁺ | 0.006633 | 0.6281 | 14.51 | 7 | 5.59 |
| K⁺ | 0.001464 | 0.7546 | 25.6 | 7 | 5.59 |
| Mg²⁺ | 0.008489 | 0.6023 | 13.12 | 7 | 5.59 |
| Cl⁻ | 0.0008445 | 0.8404 | 37.86 | 6 | 5.99 |
| DTN | 0.0009666 | 0.7329 | 25.69 | 8 | 5.32 |
| Soil moisture | 0.03435 | 0.3787 | 6.486 | 8 | 5.32 |
| Surface temperature | 0.04244 | 0.3484 | 5.813 | 8 | 5.32 |

4.2. Dependencies on surface temperature

This part presents the relations that resulted when soil water variables, soil moisture and active layer depth were run against surface temperature, precipitation data and active layer depth in linear regressions. Statistical significance was only found when variables were run against surface temperature, and therefore only these results are presented.

As can be seen in Figure 16, conductivity shows dependency on mean surface temperature (p-value = 0.025), and tends to be higher at warmer temperatures. With an adjusted r² of 0.47, a little less than half of the observations can be explained by the equation in the graph.

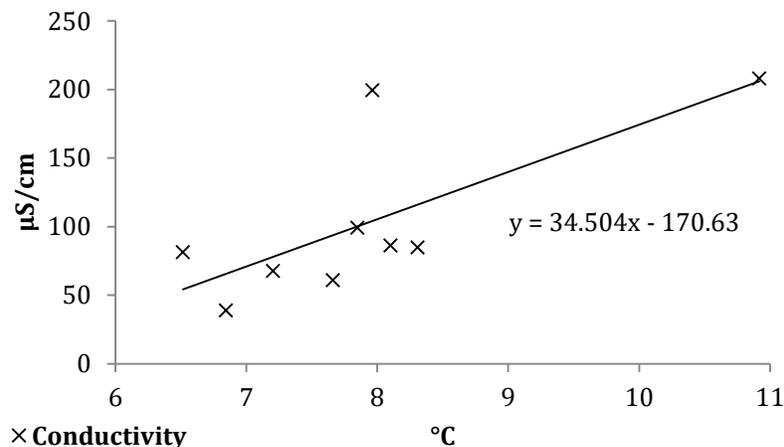


Figure 16. The dependency of the average conductivity in July and August on surface temperature, during 2004-2013. Both were measured at the site of soil water sampling, at a lowland site in NE Greenland.

Ca²⁺ and Mg²⁺, just like conductivity, show a positive dependency on surface temperature (Fig. 17). The dependency of Ca²⁺ is stronger than that of Mg²⁺, and nearly equal to that of conductivity. While conductivity has a p-value of 0.025 and an adjusted r² of 0.47, Ca²⁺ has a p-value of 0.023 and an adjusted r² of 0.48. Mg²⁺ has a p-value of 0.042 and an adjusted r² of 0.39. The remainder of the sampled ions (Cl⁻, K⁺, NH₄⁺, Na⁺ and SO₄²⁻) show no dependency on surface temperature.

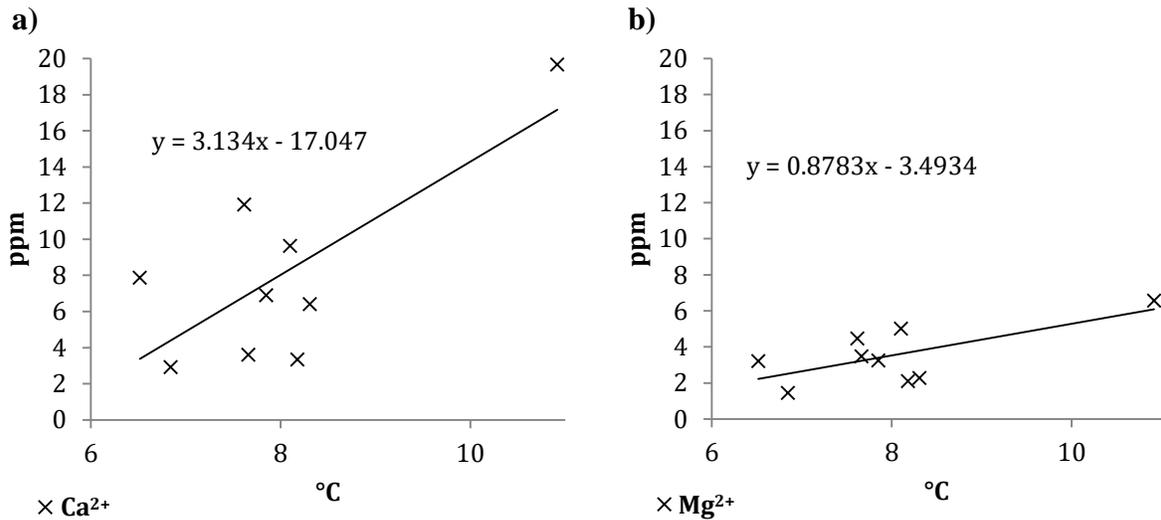


Figure 17. The dependency of average July and August ion concentrations on surface temperature at a lowland site in NE Greenland. Panel a) shows the dependency of Ca²⁺ and panel b) shows the dependency of Mg²⁺.

In table 3, more details on the statistics for the dependencies on surface temperature can be found. The statistical significances of the dependencies are generally low and relatively similar, and no variable stands out as having a particularly high significance. Also for these regressions, a target significance level of 0.05 was used for the critical values.

Table 3. More detailed statistics for dependencies on surface temperature.

| | p-value | Adjusted r ² | F-statistic | d.f. | Critical value |
|------------------|---------|-------------------------|-------------|------|----------------|
| Conductivity | 0.0248 | 0.4704 | 8.105 | 7 | 5.59 |
| Ca ²⁺ | 0.02311 | 0.4801 | 8.389 | 7 | 5.59 |
| Mg ²⁺ | 0.04189 | 0.3928 | 6.176 | 7 | 5.59 |

4.3. Correlations

In this third part of the results, statistically significant correlations between variables are presented. Correlations were in this part used instead of linear regressions, as it in these cases was not clear which variable should act as response variable and which should act as explanatory variable. This includes the tests between all soil water variables as well as the tests between *P. radicum* and the soil water variables.

Conductivity and *P. radicatum* are strongly negatively correlated ($r = -0.82$) and their developments can in Figure 18 be seen to mirror each other. The inverse relationship that could be noted in Figure 10 and 11 in the first results section is here visualized in the same graph. With a p-value of 0.002, the correlation is statistically highly significant.

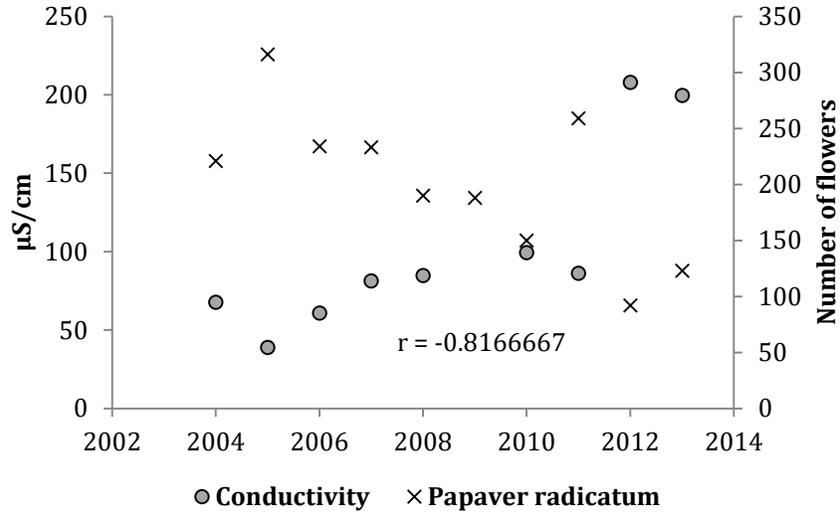


Figure 18. The negative correlation between the yearly maximum number of flowers in a High Arctic secondary population of *Papaver radicatum* at a lowland site in NE Greenland and the average July and August conductivity in the soil solution at an adjacent site. The variables are plotted against time and the correlation coefficient (r) represents the linear relationship between flowers and conductivity.

Ca^{2+} is also negatively correlated with *P. radicatum* (Fig. 19), but does not mirror the development of *P. radicatum* as precisely as conductivity ($r = -0.72$). With a p-value of 0.020, the correlation between Ca^{2+} and *P. radicatum* holds a lower statistical significance than the correlation between conductivity and *P. radicatum*. Ca^{2+} is the only ion that is correlated with *P. radicatum*.

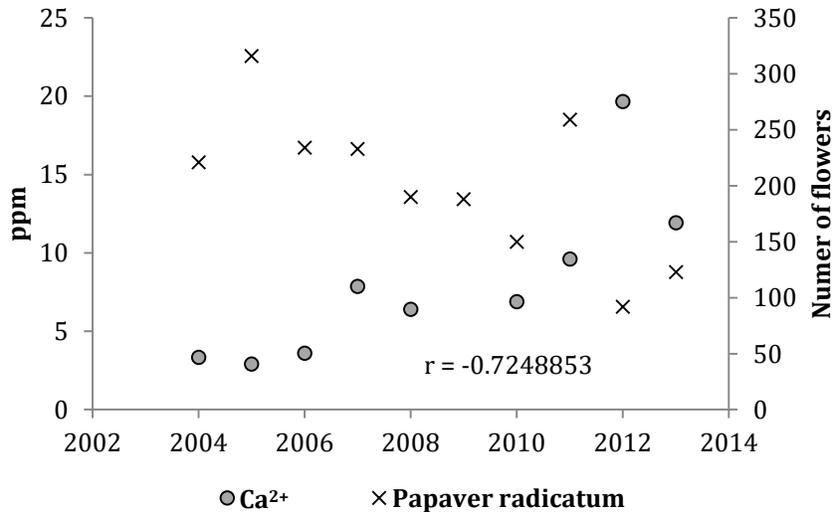


Figure 19. The negative correlation between the yearly maximum number of *Papaver radicatum* flowers at a High Arctic secondary population in NE Greenland and the average July and August concentration of Ca^{2+} , from the soil solution at an adjacent site. The correlation coefficient (r) represents the linear relationship between flowers and Ca^{2+} , which are plotted against time.

The ion concentrations are closely correlated with conductivity (Fig. 20). In Figure 20a, a close correlation between Cl^- and conductivity can be noted (p-value = 0.006, $r = 0.87$). The strongest correlation is found in Figure 20b, between conductivity and Ca^{2+} , with a p-value at <0.001 and $r = 0.96$. This relates back to Figure 19 where Ca^{2+} is the only ion that, like conductivity, correlates with *P. radicum*. Mg^{2+} and *P. radicum* correlate with a p-value of 0.012 and an r of 0.84 (Fig. 20c). The ions also intercorrelate with one another, which is accounted for in Table 5.

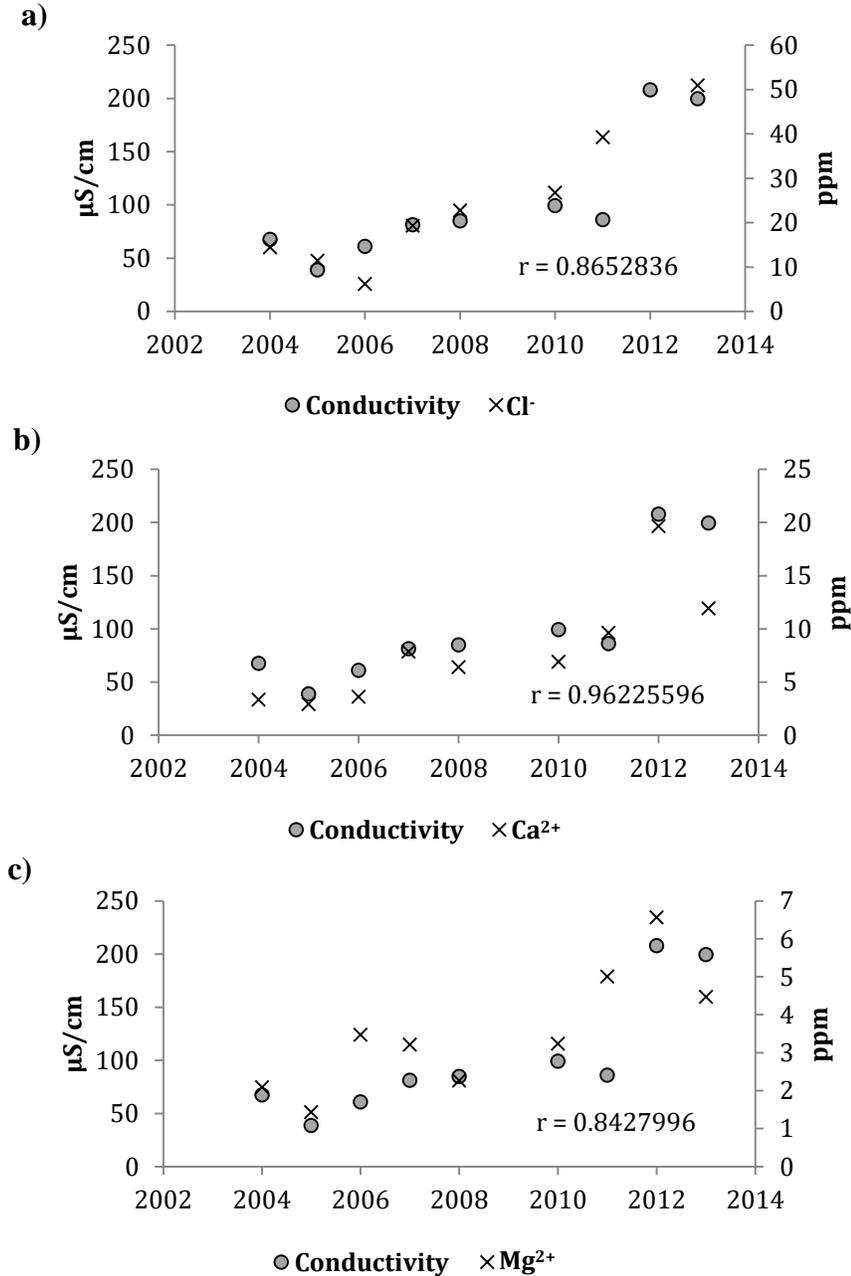


Figure 20. The positive correlations between conductivity and a) Cl^- , b) Ca^{2+} and c) Mg^{2+} . All are based on July and August averages and extracted from the soil solution at a lowland site in NE Greenland. The variables are plotted against time and the correlation coefficient (r) represents the linear relationship between the ions and conductivity.

DTN was found to correlate with several variables (Fig. 21). In Figure 21a and b, the correlations between DTN and *P. radicum* and conductivity are displayed. As DTN correlates with both, and they correlate with one another, it is not possible to say whether both are true correlations or whether DTN's correlation with one is merely an artefact of being correlated with the other. The correlation between DTN and *P. radicum* is slightly more significant (p-value = 0.035) than the correlation between DTN and conductivity (p-value = 0.042). The correlation coefficients are of nearly the same magnitude, but inversed ($r = 0.58$ for *P. radicum* and DTN, $r = -0.58$ for conductivity and DTN). DTN is the only variable that is positively correlated with *P. radicum* and negatively correlated with conductivity.

DTN correlates negatively with Mg^{2+} and positively with DOC, as can be seen in Figure 21c and d. The p-values are 0.034 and 0.042, respectively. The correlation coefficients are higher than for the correlations with *P. radicum* and conductivity; -0.70 for Mg^{2+} and 0.60 for DOC. Mg^{2+} is the only ion that has a significant correlation with DTN. In the whole results section, DOC only appears in Figure 21d. This is because no trend over time, dependency or other correlation was found.

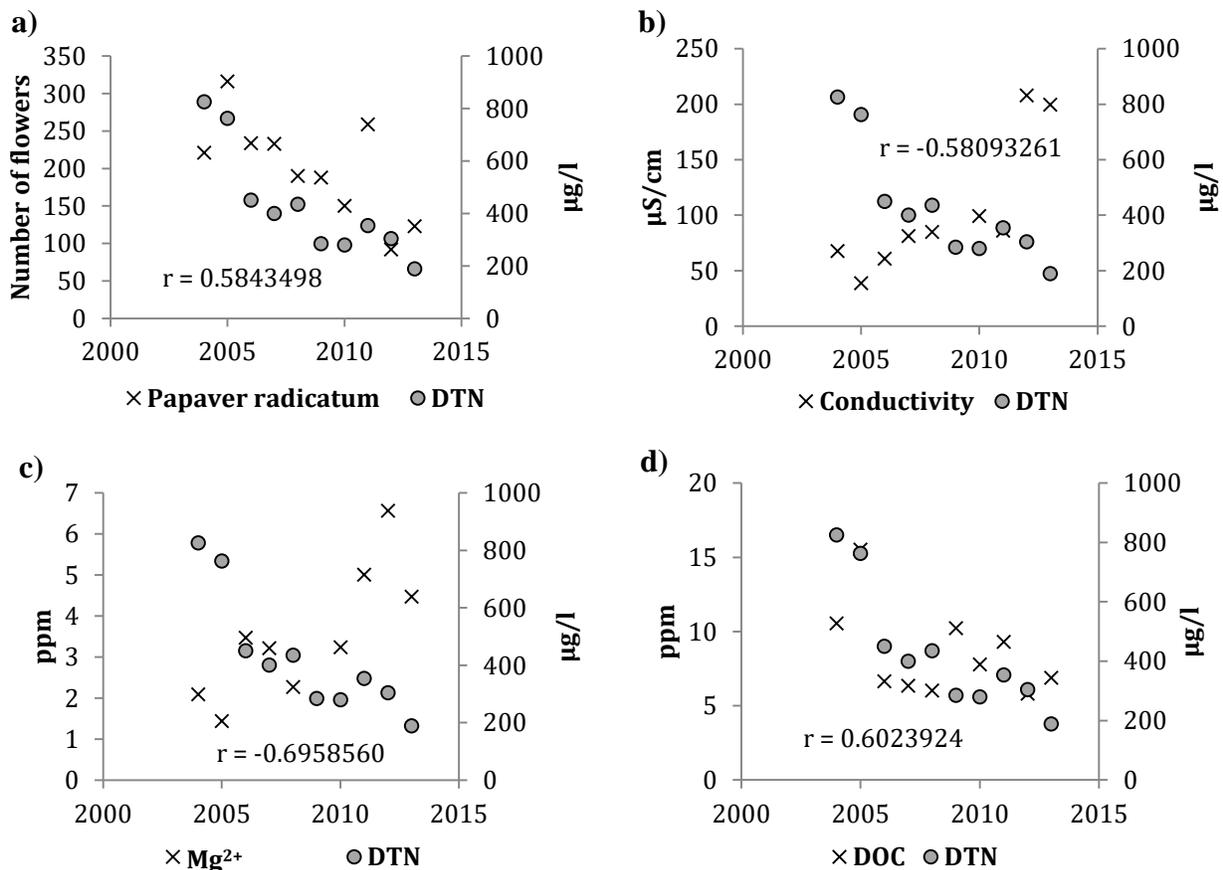


Figure 21. The correlations between dissolved total nitrogen (DTN) and a) *Papaver radicum*, b) conductivity, c) Mg^{2+} and d) dissolved organic carbon (DOC). *P. radicum* is the yearly maximum number of flowers at a High Arctic secondary population in NE Greenland, whereas the other variables are July and August averages from the soil solution samples at an adjacent site. The variables are plotted against time and the correlation coefficient (r) represents the linear relationship between the variables and DTN.

More detailed statistics for the correlations are presented in Table 4. The most significant correlation was found between Ca^{2+} and conductivity (p-value <0.001), followed by the correlation between *P. radicum* and conductivity (p-value = 0.002). The highest correlation coefficients were found for the correlations between conductivity and Ca^{2+} ($r = 0.96$) and between conductivity and Cl^- ($r = 0.87$). A target significance level of 0.025 was used for the critical values.

Table 4. More detailed statistics for correlations.

| | p-value | r | t | d.f. | Critical value |
|---|----------------|-------------|----------|-------------|-----------------------|
| <i>Papaver radicum</i> & conductivity | 0.001669 | -0.8166667 | -4.9431 | 7 | 2.365 |
| <i>Papaver radicum</i> & Ca^{2+} | 0.02043 | -0.7248853 | -2.983 | 7 | 2.365 |
| Conductivity & Cl^- | 0.005511 | 0.8652836 | 4.2282 | 6 | 2.447 |
| Conductivity & Ca^{2+} | 0.00088584 | 0.96225596 | 5.5517 | 7 | 2.365 |
| Conductivity & Mg^{2+} | 0.01181 | 0.8427996 | 3.3767 | 7 | 2.365 |
| DTN & <i>Papaver radicum</i> | 0.03522 | 0.5843498 | 2.5307 | 8 | 2.306 |
| DTN & conductivity | 0.04211 | -0.58093261 | -2.4817 | 7 | 2.365 |
| DTN & Mg^{2+} | 0.03371 | -0.6958560 | -2.6342 | 7 | 2.365 |
| DTN & DOC | 0.0415 | 0.6023924 | 2.4253 | 8 | 2.306 |

In table 5, intercorrelations between the ions are presented. The most significant intercorrelations were found between Ca^{2+} and Cl^- or Mg^{2+} , with p-values at <0.001. The least significant intercorrelation was found between Ca^{2+} and K^+ , but with a p-value of 0.010, this is still a correlation with a high statistical significance. The strongest correlation was found between Cl^- and Ca^{2+} , with an r of 0.94.

Table 5. Statistics for intercorrelations between ions.

| | p-value | r | t | d.f. | Critical value |
|-------------------------------------|----------------|-----------|----------|-------------|-----------------------|
| Cl^- & Ca^{2+} | 0.0005293 | 0.9394805 | 6.717 | 6 | 2.447 |
| Cl^- & K^+ | 0.006283 | 0.8590391 | 4.1105 | 6 | 2.447 |
| Ca^{2+} & K^+ | 0.01018 | 0.8693741 | 3.4861 | 7 | 2.365 |
| Ca^{2+} & Mg^{2+} | 0.0007788 | 0.8018336 | 5.6447 | 7 | 2.365 |

4.4. Standard deviations of the mean

In this fourth and last part of the results, the standard deviations of the soil water variables are presented in Table 6. No standard deviations could be computed for 2009, as only one sample had been taken. Also where numbers are lacking in other parts of the tables, it is due to insufficient sample size. The last row, Fraction of average, shows how the standard deviations of the different variables compare to the sample averages that were used in the data analysis. The fraction of the average is a result of dividing the average standard deviations with the average sample values. In this way, the magnitude of the fluctuations can be compared between the variables.

The highest variability occurs for Mg^{2+} , which has a mean standard deviation that composes 29% of the overall mean sample value. The standard deviations of DTN constitute the second highest fraction of the mean, at a fraction value of 0.27. The standard deviations of Ca^{2+} and K^+ compose a low fraction of the sample average, at a fraction value of 0.08 for both (Table 6).

Table 6. The standard deviation of ion concentrations, DOC and DTN in the soil solution at a High Arctic site. The fraction of the average puts the size of the standard deviations in relation to the average sample values by dividing the mean standard deviation during 2004-2013 with the average sample values from this period.

| | Cl⁻ (ppm) | Ca²⁺ (ppm) | Mg²⁺ (ppm) | K⁺ (ppm) | DOC (ppm) | DTN (µg/l) | Conductivity (µS/cm) |
|----------------------------|---------------------------------|----------------------------------|----------------------------------|--------------------------------|----------------------|-----------------------|---------------------------------|
| 2004 | 0.88 | 0.18 | 0.12 | 0.00 | 3.67 | 337.37 | 3.45 |
| 2005 | 0.58 | 0.23 | 0.46 | 0.03 | 2.83 | 63.17 | 12.02 |
| 2006 | 4.73 | 0.16 | 2.67 | 0.05 | 0.73 | 124.60 | 4.21 |
| 2007 | 1.71 | 0.33 | 0.41 | 0.09 | 1.79 | 45.28 | 8.82 |
| 2008 | 5.73 | 0.70 | 0.64 | 0.34 | 1.42 | 178.68 | 16.05 |
| 2009 | | | | | | | |
| 2010 | 5.61 | 0.71 | 0.34 | 0.06 | 0.29 | 16.15 | 9.38 |
| 2011 | 4.54 | 0.71 | 0.75 | 0.24 | 1.38 | 153.84 | 22.10 |
| 2012 | | 0.63 | 0.23 | 0.00 | 0.97 | 81.88 | 2.83 |
| 2013 | 8.58 | 1.95 | 3.30 | 0.05 | 0.95 | 72.81 | |
| Fraction of average | 0.21 | 0.08 | 0.29 | 0.08 | 0.18 | 0.27 | 0.12 |

5. Discussion

The main objective of this study was to investigate whether the development in a High Arctic population of *P. radicum* can be attributed to changes in soil conditions and surface temperature. A negative trend in *P. radicum* was found, which has been linked to changes in conductivity, Ca^{2+} and DTN (Fig. 18, 19, 21a). The changes in conductivity and Ca^{2+} show dependency on rising surface temperatures (Fig. 16, 17).

In this discussion, the soil conditions are assumed to affect *P. radicum* and not the other way around. Figure 2 and 3 show photos of Mix 1, where the soil conditions were monitored, during 2005 and 2015. No flowers of *P. radicum* can be seen in the two photos and it is therefore not likely that the plant was present in a high quantity at the site. With this in mind, there were most likely not many plants present in 2004-2013 either. Thus, there would have likely not been enough *P. radicum* during the given years to affect the soil conditions significantly at Mix 1.

5.1. Ion toxicity levels

According to Adams and Lamoureux (2005), the only two ions that normally reach high enough concentrations to cause plant osmotic problems are Cl^- and SO_4^{2+} . No trend for SO_4^{2+} has been identified in this study, and the concentration of Cl^- reaches 56.3 ppm at most, which is well below the concentration of 4000-7000 ppm that is estimated to be critical for sensitive plants (Tavakkoli et al. 2010).

Funk et al. (2004) studied how high levels of conductivity and individual ion concentrations impact the vegetation cover in Arctic conditions in Alaska. He found that the vegetation cover decreased dramatically as conductivity reached levels of above 10 000 $\mu\text{S}/\text{cm}$. The same occurred at Mg^{2+} and Ca^{2+} concentrations above 500 ppm. The K^+ threshold lay at about 100 ppm, whereas Cl^- had adverse effects on the plant occurrence first at about 5000 ppm (Funk et al. 2004). In this study, the highest conductivity was 210 $\mu\text{S}/\text{cm}$, and the top concentrations of Mg^{2+} , Ca^{2+} , K^+ and Cl^- were 7.5, 20.1, 2.1 and 56.3 ppm, respectively (Skov 2016). The sensitivity to elevated ion concentrations may vary greatly between different species. Although no specific information about the sensitivity of *P. radicum* has been found, a negative effect is very unlikely, since the levels in this study are far below the levels that have proved harmful for other Arctic plants (Funk et al. 2004).

5.2. Weathering and vegetation controls in the High Arctic

Ions are primarily made available by the weathering of parent material, which in the Arctic is regulated mainly by temperature fluctuations (Jones et al. 2010). Chemical and biological weathering is generally limited due to the low temperatures and low biological activity and instead, physical weathering is often intense. The weathering occurs in the active layer, and repeated freeze and thaw processes make the active layer a zone of intense physical disturbances (Campbell and Claridge 1992).

Arctic soils compose a harsh environment for biological activity. Due to the greatly restricted weathering of mineral materials, the release of nutrients in Arctic soils is very

slow (Campbell and Claridge 1992). The slow release of nutrients coupled with the low decomposition rates make Arctic soils strongly resource limited (Zmudczynska-Skarbek et al. 2013). The soils in Arctic regions also tend to be extremely fragile, as the low temperatures mean that only a limited number of soil processes are active and at very slow rates (Campbell and Claridge 1992).

The soil at the site has an average pH of 5.3. The lowest value during the period of this study was found in 2007, when pH went down to 4.9 (Skov 2016). In soils that are this acidic, there is a major risk for Mg^{2+} , Ca^{2+} and K^+ deficiency (Adams and Lamoureux 2005). Positive trends in these cations hence indicate a better nutrient availability in the soil. *P. radicum* has a high demand for Ca^{2+} (Nilsson 1995), meaning that the higher Ca^{2+} levels should be beneficial to the plant. In this study, a negative correlation between *P. radicum* and Ca^{2+} was found (Fig. 19). Possible explanations to this will be presented in chapter 5.4.

Higher temperatures (Fig. 15b) lead to an increase in the active layer depth (Schlesinger and Bernhardt 2013). A deeper active layer exposes greater volumes of soil to weathering, which explains the link between temperature and the positive trends in conductivity and ion concentrations (Fig. 16, 17). This is in line with earlier research, which has found that climate change brings increased soil mineralization and microbial decomposition, thereby elevating the nutrient availability (Rustad et al. 2001; Gouttevin et al. 2012).

In the High Arctic, plant distribution and abundance is mainly controlled by summer temperature on a regional scale, and by soil moisture on a local scale (Edlund and Alt 1989). But although much of the structure and function of High Arctic plant communities is controlled by water, Gold and Bliss (1995) found that plants do not appear to be water stressed even in the driest soils. In this study, soil moisture was found to decrease with time (Fig. 15a), but the negative trend in *P. radicum* showed no dependency on the decreasing soil moisture. The decrease in soil moisture in this study is in line with earlier research on the topic, as Oechel et al. (1993) concluded that in well-drained areas, drought conditions can become more prevalent as the active layer depth increases.

5.3. Nitrogen availability

Due to low decomposition rates, the availability of nitrogen in Arctic soils is low (Campbell and Claridge 1992). Nitrogen is the only mineral nutrient that cannot be derived from the weathering of rocks, so the availability of nitrogen will not increase with increased weathering rates (Sadava et al. 2009). In this study, the concentration of dissolved nitrogen in the soil has decreased significantly, in close correlation with *P. radicum* (Fig. 14, 21a).

Nitrogen decomposition rates increase with temperatures, leading to higher turnover rates of nitrogen as the temperatures become warmer (Campbell and Claridge 1992). In spite of this, studies have shown that climate change leads to a reduction of nitrogen in the soil solution, as the plant and microbial uptake of nitrogen increases faster than the

decomposition rates (Hu et al. 2001; Nie et al. 2015). This supports the findings of this study, as DTN decreases in spite of a positive trend in temperature (Fig. 14, 15a).

Warmer temperatures and increased concentrations of essential nutrients such as Mg^{2+} , Ca^{2+} and K^+ provide more favourable conditions for biological activity in Arctic ecosystems (Campbell and Claridge 1992; Jones et al. 2010). As these limiting factors on plant and microbial growth are reduced, the ecosystems instead shift toward becoming more strongly limited by other factors, in this case nitrogen. The shift in limiting factor can be an explanation for the negative correlations between DTN and conductivity (Fig. 21b) and between DTN and Mg^{2+} (Fig. 21c).

According to Forkel et al. (2016), climate change has already amplified biological activity in Arctic ecosystems. The demand for organic carbon is linked to the level of biological activity at the site, leaving less organic carbon in the soil solution when the biological activity is high (Suberkropp et al. 1976). This supports the results of this study, as the negative trend in DTN is correlated with a general decrease in DOC (Fig. 21d). For both DTN and DOC, the elevated demand from microbes and plants seems to exceed the increased decomposition rates.

5.4. *Papaver radicum*'s susceptibility to competition

P. radicum is highly vulnerable to competition from other species and relies on the occurrence of disturbances (Selin 2010). Its presence is linked to climatologic stress and active geomorphological processes (Persson 2011). According to Selin (2010), it can be characterized as a typical pioneer species. Its most favourable habitats are virgin areas with mineral soil and low competitive pressure, where it shows good growth ability and fast development (Nordal et al. 1997; Selin 2000). Due to the extremely fragile lowland soils and the high frequency of rock avalanches and other disturbances in northeast Greenland, virgin areas are frequent enough for *P. radicum* to be considered an ubiquitous species there (Bliss and Peterson 1992).

It has previously been mentioned that the conditions for biological activity became more favourable at the site during 2004-2013, which most likely led to a denser vegetation cover and a higher competitive pressure. Being highly susceptible to competition (Selin 2010), *P. radicum* was not able to compete for space and resources and therefore decreased significantly over the same time period. The increased competition for resources such as nitrogen and water, which can be linked to warmer temperatures and higher general nutrient availability, is a probable cause behind the negative trend in *P. radicum* in this study.

To estimate the future impacts that climate change may have on *P. radicum*, historical fluctuations in the plant frequency can be studied. Selin (2010) concluded that in Scandinavia, various subspecies of *P. radicum* were likely more widespread during the Little Ice Age (about 1650-1800). As the climate became warmer, the vegetation cover in high mountain areas grew denser. This led to a higher competitive pressure for the primary populations of *P. radicum* and severely diminished its population size (Selin 2010). The densification in vegetation cover that comes with the current climate change

poses a threat to High Arctic populations of *P. radicum* in a similar way. Primary populations will have to move to higher elevations, where they, naturally, will have less space. Secondary populations are threatened by the elevated competitive pressure and may decrease substantially. Climate change is however also causing the retreat of the Greenlandic ice sheet (Rignot et al. 2011), exposing new virgin areas that are suitable for colonization by *P. radicum*. Thus, the relationship between climate change and the *P. radicum* population size on Greenland is complex. This means that no general conclusions about the future status of *P. radicum* on NE Greenland can be drawn from this study.

5.5. Implications of the study

As mentioned in chapter 1, *Introduction*, *P. radicum* is suitable as a model species (Molau et al. 1996) and can, according to Selin (2010), be applied as a model species for other Arctic species that are susceptible to competition and reliant on disturbances. In order for a model species to be useful, their dependencies on and correlations with abiotic conditions must be well studied. This study has given some insight in how a secondary population of *P. radicum* can respond to changing surface temperatures and soil conditions.

This study has found a negative relationship between warmer temperatures and *P. radicum* flowers, which contradicts several previous studies. Molgaard and Christensen (1997) conducted an International Tundra Experiment (ITEX) study with *P. radicum* and found that *P. radicum* responded to warmer temperatures with an increased number of flowers. The study was performed at a similar site on west Greenland, at an altitude of 20 m.a.s.l. In ITEX studies, open-top chambers (OTCs) are used to simulate warming (Henry and Molau 1997). Levesque et al. (1997) have conducted a study of phenological and growth responses of *P. radicum* along altitudinal gradients in the Canadian High Arctic. The altitudinal gradient was used as a substitute for climatic gradients. They concluded that moderate climate warming would likely promote the growth and establishment of *P. radicum*, as long as factors such as snow-free periods and water availability do not become limiting (Levesque et al. 1997).

Conducting the study in an open area instead of in chambers and over time instead of over an altitudinal gradient has certain benefits. The OTCs that were used by Molgaard and Christensen (1997) have been criticized for causing confounding effects such as potential interference with pollination and low wind speed (Marion et al. 1997; Hollister et al. 2006; Bokhorst et al. 2013). In this study, no such confounding effects were present, as the study area was in the open. When a study is made over time instead of over altitudinal gradients, more complex feedback mechanisms can be included. The results of this study stress the importance of studying plants in their whole and correct ecological contexts, where no chambers limit important factors such as competitive pressure from other plants and where important feedback mechanisms are given time to evolve.

5.6. Potential sources of error

The analyses of soil water variables are based on a low number of samples, which means that they do not necessarily give a correct representation of the conditions throughout the sampling period (July and August). Furthermore, there is a large variation in the sample size from year to year, which means that some averages are more reliable than others. As mentioned in chapter 3, *Site description and methods*, some soil water variables could not be analysed during some sampling instances, leading to varying sample sizes for the different variables. The small sample sizes, inconsistent sampling frequencies and the short time period represent the largest source of error in this study.

The soil water sampling method is in itself debatable. The repeated creation of negative pressure on the bottles leads to a negative pressure in the suction probe. This negative pressure pulls soil water and particles into the probe, with a higher concentration of particles in this solution than in the soil water solution in general. This gives erroneous values for the concentrations, but as this study focuses on the interannual variability and the same method has been used throughout the whole period, the method is still applicable for this study.

The periods of surface temperature that the soil water variables have been compared against were adjusted to fit the sampling dates of the soil water. Although attempts have thus been made to compensate for the skewedness of some years' sampling periods, this only works if the sampling dates are distributed evenly throughout the period. When one sampling was done in the beginning of July and the remaining three samplings were done in the end of August, nothing compensates for the skewedness in the temperature average. But as the extraction of soil water is normally a slow process, the samples are generally relatively well spread out during the season. For the active layer depth, there is no skewedness, as only values adhering to the soil water sampling dates were used.

When only one soil water sample was taken during a season, only the temperature measurements from that day were included in the average. That means that these averages do not represent the general conditions during the season. Temperature measurements were overall only taken from the period between the first and the last soil water sample, so the conditions leading up to the first sampling have not been included. It was mentioned in the *Materials and methods* that there is no temperature data from before 6th of July 2004 and after 11th of July 2013. The temperature averages from these years do thus not include the entire season and do not fully represent those seasons.

The high temperature (11 °C) in Figure 16 and 17 is likely a consequence of there only being soil water data from the 9th and 28th of July during that year (2012). The samples, being taken during the peak of the summer season, yielded higher ionic strengths. However, the temperature period that the soil water variables were run against has been adapted to cover the same time period and therefore, the relationship should be correct.

The interpolation and extrapolation of the active layer depth were performed using linear equations. As the increase in active layer depth is not perfectly linear, this means that some of the values are either too high or too low. When representing July and August as a

whole, this kind of approximation still produces an average that is a good representation of the season. However, when run against soil variables that were only sampled once or a few times during the season, the approximated active layer depth may not correspond well with the actual depth. This may be a contributing factor to there not being any correlations between the average active layer depth and soil water variables.

P. radicum was not counted on the same dates during the different years, but BioBasis have made attempts to count the flowers at the same phenological time every year (i.e. when most or all flower buds have opened). This strategy should actually give a more correct representation of how the different years' conditions have impacted the plants' success rates. As Mix 1 lacks a significant amount of *P. radicum*, it is not a perfect representation of Papaver 3. Its proximity and similar elevation does however mean that factors such as climatic conditions and underlying soil characteristics should have a high level of agreement.

5.7. For further research

The size of this study is limited, which has implications for the reliability of the drawn conclusions. To improve the reliability, further research with more variables would be beneficial. An option could be to include winter conditions in the analysis, as previous research has shown that the change in snowpack characteristics influences various soil properties, e.g. water content, carbon distribution and nutrient availability (Gouttevin et al. 2012; Maurer and Bowling 2014; Semenchuk et al. 2015). Data on grazing and trampling could be included, as they represent important disturbances for *P. radicum* (Selin 2010). Furthermore, the effects of competitive pressure for pollinators and these pollinators' phenological responses to climate change could be included. The addition of precipitation data could slightly compensate for it not being possible to test soil water variables against soil moisture. If photos depicting the changes in vegetation cover at Papaver 3 during the years 2004-2013 could be accessed, this would be a helpful tool in judging the validity of the conclusions that have been drawn.

Environmental conditions during previous growing seasons can have a large impact on perennial Arctic plants (Levesque et al. 1997). To establish how the growth of *P. radicum* is related to conditions during previous years, the number of *P. radicum* in individual years could be tested against the averages of environmental variables from previous years.

As not all ions were sampled and not all of the sampled ions could be included in the statistical analyses, it cannot be disregarded that some of the left out ions may have reached toxic levels or in some other way had a significant impact on *P. radicum*. This thesis has only discussed the trends, dependencies and correlations that were found in this study, but leaves it to others to investigate other potential explanations.

6. Conclusion

This study has identified a negative trend in the number of *P. radicum* flowers between 2004 and 2013 in a secondary population at Zackenberg, NE Greenland, and concluded that the decline can be attributed to a combination of abiotic and biotic factors. An increase in surface temperature was found, which has led to a deeper active layer and a subsequent higher rate of weathering. With intensified weathering comes a higher release of ions, giving increases in Ca^{2+} , Mg^{2+} , K^+ and Cl^- . Out of these, Ca^{2+} and Mg^{2+} show a direct dependency on surface temperature. No ion reached toxic levels, and the release of cations improved the nutrient availability of the acidic soil at the site. Together with warmer temperatures, this made the site more favourable for plants and microbes, causing intensified competitive pressure for resources and space. Dissolved total nitrogen (DTN) decreased in correlation with dissolved organic carbon (DOC), as the decomposition rates did not increase rapidly enough to meet the amplified demand on nitrogen and organic carbon. The elevated competitive pressure ultimately caused the negative trend in *P. radicum*, which is highly susceptible to competition.

P. radicum can function as a model species for other Arctic plants that are vulnerable to competition and reliant on disturbances. Model species must be well studied, and this study provides insights in how *P. radicum* can respond to warmer temperatures and altered soil conditions. The number of *P. radicum* flowers has in previous studies been found to increase with warmer temperatures, which is the opposite of what was found in this study. In contrast to the previous studies, *P. radicum* was here studied in its full ecological context and complex feedbacks mechanisms were given time to develop. Although having many potential sources of error, the contrasting result of this study stresses the importance of studying how the plants develop over time in open, unmodified areas. In future research, other factors that can moderate the effects of climate change could be included, providing a fuller understanding of how *P. radicum* and similar plants will respond to climate change in the future.

7. References

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