Proxy Dating in Iceland Testing the validity of Silene acaulis as a phytometric proxy

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Proxy Dating in Iceland

*Testing the validity of Silene acaulis as a phytometric proxy*

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S.I.T. Iceland Fall, 2016
Acknowledgements

First I would like to thank my Academic Director, Ragnar Honeth, and my Program Assistant, Jennifer Smith for helping guide my project design and completion and for their support throughout the entire process.

Thank you to my advisor Maria Hildur Maack, for supporting me during my field work and the writing of my paper.

I would also like to thank Dagný, Heimir, Orri, and Hákon welcoming me into their home and family during my time in Iceland.

Lastly, thank you to my family for making it possible for me to come to Iceland and giving me constant support throughout my studies.
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Abstract
Climate change is causing drastic changes in the cryosphere, particularly in the Arctic region where average warming is 1.9 times greater than in the rest of the world due to Arctic amplification. Understanding the response of essential climate variables such as glaciers and ice caps to rapid Arctic warming is essential to predicting future changes in the Arctic region and around the world. Proxy dating methods can help construct a record of warming-induced glacial retreat in areas where long-term monitoring systems are not in place. In Arctic regions, the cushion plant *Silene acaulis* represents one of the only feasible proxies for tracking recent glacier retreat (within hundreds of years). This study uses independent control data from the Icelandic Meteorological Office’s glacier monitoring stations in the Sólheimajökull valley on the southern coast of Iceland to test the accuracy of previously constructed *Silene acaulis* growth rate curves and to determine the validity of *Silene acaulis* as a phytometric proxy for recent glacial retreat in the Arctic region. The diameters of 207 *Silene acaulis* were measured in the Sólheimajökull glacier forefield and qualitative measures of abiotic and biotic factors such as epiphyte load, patchiness, and shelter were taken. Relationships between measured diameters and substrate age were compared to predicted substrate ages from constructed growth rate curves. High levels of error were found and attributed to the lack of inclusion of abiotic and biotic factors in constructed growth rate curves. Further study on the ecology of *Silene acaulis* is recommended to increase its accuracy as an Arctic phytometric proxy.
1. Introduction

1.1 Importance of proxy monitoring

In 2014, the Intergovernmental Panel on Climate Change (IPCC) stated that anthropogenic emissions have created unequivocal warming of the climate, leading to changes in the atmosphere, cryosphere, and hydrosphere that are “unprecedented over decades to millennia.” With changes occurring so rapidly, observations and monitoring are critical to assessing the current climate system, predicting future changes, and developing policy response (Bojinski et al., 2014). In 2012, the Global Climate Observation System (GCOS), a part of the World Meteorological Office (WMO) created a list of fifty atmospheric, oceanic, and terrestrial “essential climate variables” which are important within the climate system and are feasible to monitor. While monitoring systems like GCOS are essential, they have not always been in place and they do not have the capacity to monitor everything that is changing. Proxies can be used to extend current monitoring into the past, so as to create a more complete record, as well as to obtain information from regions that are not monitored under current programs.

Creating a complete record is even more important in the Arctic region, where climate changes are happening at a faster rate than the rest of the world. Average warming in the arctic region (60°N–90°N) is 1.9 times greater than average warming in other regions (Serreze and Barry, 2011). Increased warming in the Arctic is causing drastic changes to the cryosphere, including ice caps, and glaciers – both of which are labeled as essential climate variables by GCOS. Many different kinds of proxies have been used to date glacial retreat. Isotope ratios and pollen can show glacial retreat over a large area and on a scale of thousand to tens of thousands of years (Dorn, 1991; Gosse et al., 1995; Bernabo and Webb, 1997). While these methods can be useful, phytometry can offer more recent retreat information on a finer spatial and temporal scale (le Roux and McGeoch, 2004), which is useful for tracking recent retreat of specific glaciers and ice caps. The two most commonly used phytometric methods are dendrochronology and lichenometric dating. However, these methods are not always useful for dating recent changes in Arctic environments. Trees and lichens are not always present in Arctic environments. In addition, lichens are often used for dating on the scale of thousands of years, rather than hundreds.

The relatively unexplored method of cushion plant dating could potentially fill the niche requirement of monitoring recent glacial retreat in Arctic landscapes, where dendrochronology and lichenometric dating are not feasible. In order to be broadly applied, the cushion plant dating technique has to first be tested against verified dates. Iceland is an ideal location for this kind of testing. Silene acualis, the cushion plant used for dating in the northern hemisphere, is widespread in Iceland (Kristinsson, 2013). In addition, the recent glacial fluctuations in Iceland have been carefully monitored by the Icelandic Meteorological Office (IMO) since 1930, providing accurate control dates for most of the glacial forefields in Iceland.
1.2 Aims of study

This study aims to determine the validity of *Silene acaulis* as a phytometric proxy in Arctic regions, where it could be used to create a more complete record of warming-induced glacier retreat as well as to expand monitoring into areas where long-term monitoring is not possible. This study tested the validity of *Silene acaulis* as a phytometric proxy by assessing the accuracy of growth rate curves that have been constructed for *Silene acaulis*. Accuracy was determined by measuring the diameters of *Silene acaulis* in the Sólheimajökull valley and comparing predicted age-size relationships to independent dating controls from three IMO monitoring stations. Some qualitative measures of abiotic and biotic factors were taken, such as epiphyte load, patchiness, and shelter in order to determine whether or not they may have an effect on the growth rate curve, although potential effects were not quantified. The accuracy of constructed growth rate curves as well as the effects of biotic and abiotic factors were used to determine whether or not *Silene acaulis* can currently be used as an accurate phytometric proxy in Iceland and therefore in other Arctic regions and what further research should be done.

2. Context

Cushion plant dating bears the most similarity to lichenometric dating due to shared justifications and methodologies. In fact, both were proposed by Beschel (1950) as potential proxies for dating newly exposed landscapes, but only lichenometric dating has gained popularity. While some hundreds of papers have used the technique of lichenometric dating to age a newly exposed substrate (Osborn et al., 2015), only four studies have attempted to do the same with cushion plants, resulting in very little literature on the subject. Therefore, this section will summarize the justifications for and critiques of the lichenometric dating technique, review why the justifications for lichenometric dating also apply to cushion plant dating, outline the work that has been done with cushion plant dating so far, and finally, discuss which critiques of the lichenometric dating technique can also be applied to the cushion plant dating technique.

2.1 Justification for Lichenometric Dating

Lichenometric dating has gained popularity since 1960 as a relatively inexpensive and easy method of dating surficial features around the world (Osborn et al., 2015). The justification for using lichens as a proxy for substrate age is based on three basic assumptions stated by Calkin and Ellis (1980, 247):

1) Newly deposited material is free of lichen thalli;
2) colonization occurs shortly after the surface or deposit is formed; and
3) subsequent growth (increase in thallus diameter) occurs with a predictable pattern and, within a general region with the same macroclimate, is a function of time passed since colonization.
Typically lichenometric dating methods fall between two categories. “Indirect lichenometric dating” uses known surface age to calibrate thallus sizes, while “direct lichenometric dating” constructs growth rate curves from direct measures of growth such as lichen ‘growth rings’ (Armstrong, 2015). Lichenometric growth rate curves are used to determine the age of a lichen of a given size, and therefore the approximate minimum age of the substrate. When constructing lichen growth rate curves, most studies only take into account the largest lichens in the sample area based on the assumption that the largest lichens represent lichens growing under optimal conditions and an optimal growth rate, and therefore are the oldest lichens (Beschel, 1961).

2.2 Critiques of Lichenometric Dating

There has been a long history of published criticism against lichenometric dating techniques (Jochimsen, 1973; Webbers and Andrews, 1973; Osborn et al., 2015). Jochimsen (1973) published one of the first and most comprehensive critiques, in which she concluded that variable lichen growth rates due to differences in micro-environment made growth rate curves invalid. She also lists identification difficulties and plastic morphology as issues. In addition, she addresses the problem of uncertain lichen colonization dates. For example, when using lichens to date a moraine, it is assumed that all of the debris in the moraine was exposed as a result of glacier retreat. However, it is possible that some of the debris that forms the moraine was on the landscape and exposed to the surface prior to glacier retreat, and was simply pushed into the moraine by the snout of the glacier. Some of these lichens would predate the retreat of the glacier and therefore provide an inaccurate measure of age for the moraine.

The most recent critique of lichenometric dating was published in 2015 by Orson et al. They questioned the validity of numerical ages derived from lichenometric dating based on lack of agreement on practice, ignored or misunderstood ecological considerations, and problems with constructed growth curves.

Orson et al. (2015) lists several issues with the practice of lichenometric dating, including lack of agreement on range of utility, measurement methods, dating handling, and potential errors. Scientists have claimed that lichenometric dates can be used for a range of 100 to 10,000 years, with no agreement on what is realistic. There is also little agreement how many lichens should be sampled to create a valid growth rate curve. The basic assumptions of lichenometric dating suggest that only the largest lichens should be measured, as they are the oldest individuals in the population and will therefore give the most accurate age for the substrate. However, sampling only the largest lichens shrinks the sample size drastically, making the data statistically weak. The plastic morphology of lichens has made deciding which aspect of the lichen is the most accurate measure of growth problematic. Some studies have measured the largest diameter, while others have measured the smallest. In some cases studies have made up new measures of growth, such as the diameter of the largest circle that can fit inside the lichen. With no agreement on the practice of lichenometric dating, there can be little agreement on the accuracy of its results.
Orson et al. (2015) also states that lack of ecological considerations could affect the validity of constructed growth rate curves. Variable micro-environments can cause different rates of growth, as stated by Jochimsen (1973) but mortality rates and thallus crowding can also be important factors. Mortality rates in particular could easily violate some of the most basic assumptions of lichenometric dating, i.e. that the lifespan of the original colonists is longer than the age of the substrata and therefore that the largest thalli in a population represent the original colonists. If the largest individuals do not represent the original colonists, then the error for minimum age estimates becomes much larger.

Orson et al. (2015) lists six potential problems with the construction of lichen growth rate curves. First, independently determined control points may not be robust. In many cases, control points are determined by other proxy dating methods which are not necessarily more reliable (McCarthy, 1992). In addition, it’s often difficult to find independent controls of different ages in areas with the same micro-environment. Another problem is the variability of environments over time (particularly over the >1000 year lifespan of a lichen) which may cause variations in growth rate. Problems also lie with grouping different species (with different growth rates) together, and with extrapolating curves beyond gathered data.

2.3 Justifications for Cushion Plant Dating

‘Cushion plant’ is a growth form that describes 1,309 species across 272 genera (Aubert et al., 2014). Cushion plants were first defined in 1939 in Rauh’s typology (as cited in Box, 2012) as “perennial herbaceous or woody, mostly evergreen plants with well-developed allorhizal root systems.” They have special adaptations, such as a radial, compact, low growth form, heavily cutinized leaves, and internal disposal of all waste tissue that make them particularly well suited for cold, windy environments. They are most commonly found in arctic or alpine regions (Aubert et al., 2014).

The potential use of cushion plants for phytometric dating comes from their fulfillment of three qualifications for lichenometric dating. First, they are not already present in a newly exposed landscape. In fact, cushion plants fulfill this requirement better than lichens because they have to grow on exposed ground. It is impossible for cushion plants to grow on a rock that the glacier is pushing in front of it. Second, cushion plants are able to colonize recently exposed landscapes quickly. *S. acaulis*, in particular, has been shown to be one of the early colonizers of Arctic landscapes (Griggs, 1956, Beschel 1973). *S. acaulis* has been found on proglacial landscapes within 10 years of glacier retreat (Beschel and Weidick, 1973: Worsley and Ward, 1974). Third, the radial growth of cushion plants is constant and predictable. In addition, cushion plants have the potential to be used for proxy dating in environments where lichen growth is stunted or impossible, such as volcanic landscapes with small and easily weathered substrata (Carrara and Andrews, 1973).
2.4 History of Cushion Plant Dating

Despite the potential for using cushion plants as phytometric proxies, only four authors have attempted to create growth-rate curves for them. All work has been done on two types of cushion plants: *S. acaulis* in the northern hemisphere (Benedict, 1989; McCarthy, 1992) and *Azorella selago* in the southern hemisphere (Frenot, 1993; le Roux and McGeoch, 2004).

2.4.1 *Silene acaulis*

The first growth rate curves for *S. acaulis* were created by Benedict (1989) based on studies done in the Colorado Front Range. Benedict created both a direct and an indirect growth rate curve. The direct curve was created by monitoring the growth of twenty-seven *S. acaulis* on two moraines over two years. The indirect curve was created by measuring the maximum diameters of *S. acaulis* over seven historically dated moraines. Both growth curves are sigmoidal, showing that *S. acaulis* grows slowly at first, reaches a maximum growth rate of 2-3 cm per year, and then decreases again as the plant approaches its maximum diameter. Benedict concludes that the most accurate use of *S. acaulis* would be for providing the minimum age of landforms or erosional features up to 100 years old.

![Figure 1](image_url)

Figure 1 – a) *S. acaulis* in Sólheimajökull forefield. b) Cushion growth form of *S. acaulis* with deep taproot (Illustration by Ernest Flammarion, 1907).

McCarthy (1992) created preliminary growth curves for *S. acaulis* in the Canadian Rockies based on the work done by Benedict (1989) in the Colorado Front Range. McCarthy measured the maximum and minimum diameters of the largest *S. acaulis* found in four glacial forefields.
Wherever *S. acaulis* were measured, McCarthy also dated the area using independent techniques such as lichenometric dating. He then used these data to form a growth rate curve for the minimum average growth-rate based on maximum diameters. McCarthy’s growth rate curve was slightly different than Benedict’s curve but also showed sigmoidal growth. McCarthy concludes that cushion plant dating has potential, but that it should be used as a supplementary method until further study is done to “define the ecology and relative growth rates of *S. acaulis* subspecies” and to “test the sampling methodology and assumptions used to interpret cushion-diameter-substrate-age data.” (McCarthy, 1992, 55).

2.4.2 Azorella selago

The study of using cushion plants for proxy dating in the southern hemisphere began with Frenot et al. (1993), who used *A. selago* to measure glacial fluctuations in the Kerguelen Islands (49°30'S-69°15'E). Sixty-five plants were measured in the outwash plains between moraines. Maximum diameter, height, diameter of the root neck and the number of shoots were measured and recorded for each plant. The number of plants measured was limited by the destructive nature of the methodology in a conservation area. The study also measured radial growth over the previous three years, although it was unclear how this was accomplished. Based on these measurements, a linear relationship was found between diameter of the cushion and height of the cushion as well as diameter of the cushion and diameter of root necks. Therefore, Frenot et al. (1993) states that a simple measure of the diameter of the cushion is a sufficient measure of growth.

Unlike Benedict (1989) and McCarthy (1992), Frenot et al.’s (1993) model was based solely on a direct measure of growth rate, and attempted to track glacial fluctuation, rather than assign an age to a specific glacial landform. Frenot et al (1993) found that growth rate was independent from plant size, and therefore created an equation for growth rate modelling:

\[
\text{Age (yr)} = \frac{\text{Maximum plant diameter (mm)}}{\text{Growth rate (mm/yr)}} + 10 \text{ years}
\]

Le Roux and McGeoch (2004) continued working with *A. selago* on Marion Island (46°55'S, 37°45'E). The goal of the study was to determine the validity of Frenot et al.’s (1993) phytometric model for accurate age estimates of *A. selago* on a different island and to quantify the effects of spatial variability on the accuracy of the model. The study attempted to quantify the relationship between plant growth rate, plant size, and abiotic and biotic variables in order to include those variables into the Frenot et al. (1993) growth rate model. Le Roux and McGeoch (2004) supported Frenot et al.’s (1993) conclusion that growth rate is independent of plant size for *Azorella selago*. However, they also found that growth rate is heavily dependent on abiotic and biotic factors such as altitude and epiphyte load. With these variables included in the growth model, Le Roux and McGeoch (2004) concluded that *A. selago* could be used as a phytometer with an age error of 2-15 years.
2.5 Potential Critiques of Cushion Plant Dating

Some of the critiques that apply to lichenometric dating can be solved by cushion plant dating. Cushion plants are vascular plants with deep root systems. Therefore cushion plants found in newly exposed landscapes have mostly likely colonized the area since exposure and were not already present on the landscape. This is not always true of lichens. There is also a much lower likelihood of species misidentification and species grouping in cushion plant studies as compared to lichen studies. The papers that have been written on cushion plant dating agree that cushion plant dating has a utility range of hundreds of years. This shorter lifespan compared to lichens also means that extrapolated growth curves have less of an error in age estimates, as they cover a shorter period of time.

One of the most important critiques which could potentially be applied to cushion plant dating is the lack of all relevant ecological considerations. Le Roux and McGeoch (2004) were able to incorporate some biotic and abiotic factors into their model, but there is not a complete understanding of the effects varying micro-environments might have growth rate of Azorella selago. The studies for S. acaulis did not incorporate any abiotic or biotic variables into their growth rate curves, leaving a high potential for error. None of the studies have taken mortality rates into consideration. Although it is possible that this does not present as large an issue as it does in lichenometric dating due to the much shorter lifespan of cushion plants, it could still create large dating errors if the plants have a shorter lifespan than believed. The impacts of environmental variability over time are also probably lessened by the shorter lifespan of the cushion plants.

Another potential critique of the cushion plant dating technique is the lack of agreement on which plant measurement provides an accurate measurement of growth. Frenot et al. (1993) found that there was a linear relationship between plant height, diameter, and root stem width in A. selago therefore concluding that any of these could be used as an accurate measure of growth. However, this conclusion has not been verified for other populations of A. selago and there has been no work done to show that it can also be applied to other plants such as S. acaulis. In fact, recent research has concluded that S. acaulis can have a plastic morphology depending on altitude. At lower altitudes it maintains a flat, low, mat-like morphology, whereas at higher altitudes it becomes more compact and the height of the cushion increases (Bonanomi et al., 2016).

Similar to the studies on lichenometric dating, none of the studies on cushion plant dating have had sufficient control data. Control points have been based on lichenometric data, estimated glacial retreat rates based on meteorological data, or models, none of which are robust. Without robust control points, it’s impossible to verify growth curves or to check errors.
3. Methods

3.1 Study Site

Sólheimajökull was chosen as a study site because it has a long history of IMO monitoring (annually since 1930) and therefore has the potential to provide robust independent control points for cushion plant dating. Sólheimajökull is a non-surgeing temperature glacier of the Mýrdalsjökull ice cap in southern Iceland (63°31'00.48"N, 19°22'00.12"W). The region experiences much milder temperature than its sub-Arctic location would suggest due to a branch of the Gulf Stream, the Irminger Current, which runs along Iceland’s southern coast. Winter sea surface temperatures along the southern coast average 2°C, while the surface temperature on land typically averages 0°C (University of Iceland, n.d.).

Sólheimajökull is covered with supraglacial debris from the eruption of Katla in 1918 and the jökulhlaup in 1999. There are steep bedrock valley slopes, which include a bedrock outlier called Jökulhaus. The terminus of the glacier sits in an ice-contact lake. Sólheimajökull has been retreating since the Little Ice Age, excluding a brief period of advance between 1970 and 1995. (Slomka and Eyles, 2015). Sólheimajökull has been monitored by the IMO since 1930. There are three different monitoring sites present in the valley, which monitor Austurtunga (the east tongue), Jökulhaus (glacier header), and Vestertunga (the west tongue.)

Figure 2 – 2010 Google Earth photo of Sólheimajökull with IMO monitoring stations and corresponding transects: 1 = Austurtunga, 2 = Jökulhaus, 3 = Vestertunga
3.2 Silene acaulis

*Silene acaulis* is one of the most common plants in Iceland with a wide distribution. It often grows in sandy or gravelly soil on exposed locations on hills and rock ledges. It forms compact, rounded tussocks, with a deep taproot, bristly leafy shoots and short-stalked flowers. Pinkish flowers are typically 8-10mm wide with five free petals. Leaves are linear (5-15 mm long, 1-2 mm broad), sharp-pointed, and form in rosettes with hairs along the margins. *S. acaulis* flowers from May to June and the leaves turn red-brown in the winter (Kristinsson, 2013).

3.3 Plant measurements

Measurements were taken along three 1km transects in the Sólheimajökull valley, corresponding to the IMO monitoring sites (Figure 2). *S. acaulis* was surveyed along each transect by measuring all plants seen within 5m of either side of each transect. Every 100m, the GPS point and elevation was recorded, and all *S. acaulis* found within a 10m strip perpendicular to the transect from one side of the valley to the other were measured.

![Figure 3](image)

Figure 3 – a) Example of a non-patchy cushion with an epiphyte load of 3 b) A patchy cushion with an epiphyte load of 2 c) a protected cushion with an epiphyte load of 2
For each *S. acaulis* plant, the largest diameter and the diameter perpendicular to the largest diameter were measured (Benedict, 1989; McCarthy, 1992). Plant diameters were measured to the nearest centimeter with metal calipers so as to be comparable to the measuring techniques of Benedict (1989). If the plant was larger than the calipers, it was measured with metal rods placed perpendicular to a ruler laying on the ground next to the plant (McCarthy, 1992).

Qualitative measures of some of the abiotic and biotic factors affecting plants were also taken. Epiphyte load was quantified on a scale of 0-3, with 0 meaning there was no epiphyte load and 3 meaning that the plant was completely overgrown with other species. *S. acaulis* plants that were completely surrounded by other plants were also considered to have an epiphyte load. *S. acaulis* plants were determined to be “patchy” or not based on whether or not their branch system was exposed, or if they had complete leaf cover. Plants were labeled “protected” if they had obvious shelter from nearby rocks (Figure 3).

### 3.4 Independent dating control

The age of the substrata was determined using the glacial retreat information from the three IMO Sólheimajökull monitoring stations. The retreat information from these stations, which spans the period of 1930-2010, was mapped onto the 2010 historical image of Sólheimajökull in Google Earth. Information for areas that were exposed prior to 1930 was obtained from the moraines marked out in 2015 by Slomka and Eyles. Younger moraines mapped by Slomka and Eyles (2015) were also used to verify the retreat information from the IMO stations. GPS data from the three transects were mapped into Google Earth and compared to the moraine and retreat dates to determine an approximate age for the substrata.

For Transect 1 and 2, only glacier retreat information was considered in dating substrata. This method did not take into account rock slides or floods that may have occurred. For Transect 3 the extent of the 1999 jökulhlaup (Slomka and Eyles, 2015) was taken into consideration in determining the age of the substrata.

### 3.5 RStudio Analysis

#### 3.5.1 Age predictions

Linear regressions were used to analyze the correlation between diameter of the plants and actual age of the substrate as well as the diameter of the plants and the predicted age of the substrate according to the growth curves of Benedict (1989) and McCarthy (1992). Due to the assumptions that the largest plants represent the oldest in a population and the plants growing under optimal conditions, Benedict (1989) and McCarthy (1992) used only the largest plants to create their growth curves. Therefore, the linear regressions tested only the largest two diameters measured in every 100m of each transect for a correlation with the substrata age.
3.5.2 Environmental variables

Unlike the age predictions, the statistics for the effect of environmental variables were run with all of the measured *S. acaulis* in order to measure the effects on the entire population as well as to make the statistics more robust.

Because the premise for using cushion plants as phytometers depends on the predictable pattern of their radial growth, measured *S. acaulis* were first tested for roundness. The roundness of each plant was determined by dividing its diameter by its perpendicular diameter. Linear regressions were then run between roundness and cushion diameter to see if there was a correlation. Roundness was also tested against epiphyte load and patchiness using box plots.

Effects of patchiness and epiphyte load on diameters were tested with boxplots created in RStudio. The relationships between the age of the plants and the age of the substrate were measured using regressions in RStudio, assuming that the plant diameters were a sufficient measure of age and that the tracked glacial retreat is a sufficient measure of substrate age.

Relationships between the diameters of the plants and the amount of moss present as well as the diameters and the roundness were also tested using regressions in RStudio.

4. Results

4.1 Summary of results

There were large discrepancies between the results of each of the transects. The most plants (135) were measured in Transect 1. Transect 2 was only 600m long and fewer plants (67) were found than in Transect 1. No plants were found in Transect 3, which ran along a floodplain. A summary of the plant measurements can be seen in Table 1. The age-size relationship of plants in Transect 1 and 2 did not match well with predicted age-size relationships from the growth curves of Benedict (1989) and McCarthy (1992). Errors ranged between 0 and 80 years. There was not an obvious correlation found between diameter and epiphyte load or patchiness in any of the transects. Some of the largest plants measured were sheltered, particularly in Transect 2, which could have had a large effect on the accuracy of the constructed growth rate curves.

4.2 Transect 1 (Austurtunga)

Transect 1 began ~20m from the glacier at 268m of elevation. For the entire transect, the substrate was made up of glacial till with clast sizes of sand to gravel with some larger boulders. Over the course of transect 1, there was a loss of 140m of elevation, which was distributed fairly evenly. The transect followed the course of a river, and lay between two slopes for the first 900m. The majority of plants were found on these slopes. The last section was in a flood plain. Within the first 200m of transect 1, the ground was mostly bare except for small clumps (3-4cm) of *Saxifraga cespitosa* and *Racomitrium lanuginosum*. The *R. lanuginosum* became much more prevalent as the distance from the glacier increased. In many places toward the end of the transect *R. lanuginosum*
carpeted the ground. The first woody plants (*Empetrum nigrum*) began to appear ~500m away from the glacier.

One hundred thirty-five *S. acaulis* plants were measured across the entire transect. No *S. acaulis* were present within 200m of the glacier, where the minimum substrate age was between 0 and 12 years old. Between 200m and 500m from the glacier, the substrate was 12-18 years old and only four *S. acaulis* were found, none of which were larger than 22cm. Between 500m and 800m away from the glacier the substrate had a minimum age of 70-82 years and an average of nineteen *S. acaulis* were found per every 100m. The average for the largest plants in the 500m-800m range was 44.6cm. Between 800m and 1000m away from the glacier an average of 36.5 plants were found per 100m and the largest plants had an average diameter of 53.7cm. At 1000m, only one *S. acaulis* plant was found, which had a diameter of 27.5cm. Between 800 and 1000m the minimum substrate age was 86-90 years (Table 1).

**Table 1**  
**Summary data of *S. acaulis* plant measurements**

<table>
<thead>
<tr>
<th>Site</th>
<th>Distance from Glacier (m)</th>
<th>Elevation (m)</th>
<th>Approx. Min. Surface Age (yrs)</th>
<th>Number of Plants</th>
<th>Largest Cushion Diameters (mm)</th>
<th>Smallest Cushion Diameter (mm)</th>
</tr>
</thead>
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Total: 207

*Protected

A slight correlation was found between the size and roundness of a plant, where plants with larger diameters were slightly rounder. However, there is too much variance to show a significant relationship (Appendix 1, Figure 3). There was not a significant correlation found between patchiness and diameter or between epiphyte load and diameter (Appendix 1, Figures 1 and 2).
The *S. acaulis* plants measured in Transect 1 showed a strong correlation between substrate age and plant diameter for the largest plants. In addition, no plants (including protected plants) had high leverage over the data (Figure 4A). However, the measured relationship between the maximum *S. acaulis* diameters and age of the substrate did not match well with the relationship predicted by Benedict (1989) and McCarthy’s (1992) *S. acaulis* growth rate curves. There were errors of 0-50 years and 0-70 years respectively. (Figure 4B). The slope of the regression line for the measured *S. acaulis* plants is much lower than the slopes of Benedict (1989) or McCarthy’s (1992) regression lines, showing that the plants measured on older substrates are smaller than predicted.

![Graphs showing relationship between diameter and substrate age](figure4.png)

Figure 4 - a) Relationship between diameter and substrate age for the largest *Silene acaulis* plants. Shows that plants get larger diameters as they get older, and protected plants do not have higher leverage than others. R-squared = 0.6375, p-value < 0.01. b) Relationship between diameter and substrate age for the largest *Silene acualis* plants compared to Benedict (1989) and McCarthy’s (1992) predictions. Measured plants are smaller than predicted given the substrate age with an error range of 0-50 and 0-70 years respectively. Measured regression line statistics are the same as 4A, Benedict and McCarthy’s R-squared values are 0.97 and 0.92 respectively, p-values are both < 0.01.

4.3 Transect 2 – Jökulhaus

Transect 2 began relatively far away from the glacier (~200m) due to impassable terrain and ran for 500m until it was intercepted by the road. Based on a visual scan of the area, there were no plants present between the glacier terminus and the beginning of the Transect 2. Similar to Transect 1, the substrate was made up of glacial till with clast sizes of sand to gravel, with some larger...
boulders scattered throughout. The transect began at an elevation of 173m and ran along the northern side of Jökulhaus, with a total loss of 50m of elevation.

The first 300m of the transect followed a river bed in a steep valley, with debris from rockslides along the valley walls and a coating of *R. lanuginosum*. Within the first 100m of the transect, twelve *S. acaulis* plants were found, with the largest plants averaging 52.65cm. The largest plants in this section were all growing among rockslide debris and were very protected. Between 100m and 300m, an average of 18.5 *S. acaulis* plants were found per 100m, with the largest plants averaging 31.15cm. Between 300m and 400m there was a wide area with little vegetation, although the side of Jökulhaus had more rockslide debris and *R. lanuginosum*. There were only two *S. acaulis* plants found in this section but they averaged 41.2cm in maximum diameter. Between 400m and 600m the transect went down a hill covered in *R. lanuginosum* and *Empetrum nigrum*. There was an average of 10 plants found per 100m in this section with the largest plants averaging 27.4cm in maximum diameter.

![Transect 2 - Maximum Diameters (cm) vs. Substrate Age (yrs)](image)

Figure 5 - a) Relationship between diameter and substrate age for the largest *Silene acaulis* plants. Shows correlation between older substrate age and smaller diameters, although it is statistically weak, and high leverage points are all protected plants. R-squared = 0.07, p-value = 0.2. b) Relationship between diameter and substrate age for the largest *Silene acaulis* plants compared to Benedict (1989) and McCarthy’s (1992) predictions. Measured plant have a negatively sloped regression line compared to positive slopes for predicted diameters. Error range from 0-50 and 0-80 years respectively. Measured regression line statistics are the same as 4A, Benedict and McCarthy’s R-squared values are 0.97 and 0.95 respectively, p-values are both < 0.01.
A slight correlation was found between the size and roundness of a plant, where plants with larger diameters were slightly rounder. However, there is too much variance to show a significant relationship (Appendix 1, Figure 4). There was not a significant correlation found between patchiness and diameter or between epiphyte load and diameter (Appendix 1, Figures 5 and 6).

The *S. acaulis* plants measured in Transect 2 showed a very weak correlation between substrate age and plant diameter. In addition, three plants (all of which were heavily protected) were statistical outliers (Figure 5a). The measured relationship between the maximum *S. acaulis* diameters and age of the substrate for Transect 2 did not match at all with the relationship predicted by Benedict (1989) and McCarthy's (1992) *S. acaulis* growth rate curves (Figure 5b). There was an error range of 0-50 years and 0-80 years respectively. The regression line for the measured *S. acaulis* plants had a negative slope, compared to positive slopes for Benedict (1989) and McCarthy's (1992) regression lines. Although the regression line shows a trend of smaller plant diameters with higher substrate age, it is not statistically significant.

4.4 Transect 3 - Vesturtunga

Transect 3 began at the terminus of the glacier, on the southern shore of the glacial lake. It ran 1000m back from the glacier along the glacial floodplain. Like the first 2 transects, the ground was made up of glacial till with clast sizes of sand to gravel, with larger boulders scattered around.

There were no *S. acaulis* found along Transect 3.

5. Discussion

The results of this study show the potential benefits as well as the many issues that would have to be solved before *S. acaulis* can be used as a reliable phytometric dating tool. The potential for *S. acaulis* can be seen in the results from Transect 1. Although the ages do not match well with the ages predicted by Benedict (1989) and McCarthy (1992), there was a strong correlation between the size of the plants and the age of the substrata. This correlation suggests that an accurate model is possible if further research is done to include relevant abiotic and biotic variables into the growth models.

However, Transects 2 and 3 show the issues with using *S. acaulis* as a phytometric dating method. The negative slope in the regression curve for Transect 2 show that there are variables that have not been accounted for in the growth rate curves which can severely throw off the accuracy of predicted dates. The lack of plants in Transect 3 shows the potential for soil moisture in glacial forefields to be a limiting factor in tracking recent glacial retreat.

5. 1 Abiotic variables

Immediate shelter from nearby rocks was the main abiotic variable taken into account while measuring. While in Transect 1 this factor did not appear to have a large effect on the data (e.g. protected plants did not have high leverage over the data), in Transect 2 protected plants had high leverage over the data. The *S. acaulis* with a 57.1cm diameter that was found within the first 100m
of Transect 2 was the largest plant found in the entire study, and also one of the most sheltered. The presence of such a large plant within the debris from a rock slide proves that there are at least two abiotic factors that could affect the data. First a location in a sheltered setting probably leads to a higher growth rate, creating large errors in predicted growth rates. Second, there are factors other than glacial retreat which need to be considered in dating the substrate. A rockslide that occurs after glacial retreat could affect the predicted ages.

Although it was not quantitatively measured, soil moisture also appeared to play a large role in whether or not *S. acaulis* could be found in a given area. In Transect 1, most of the *S. acaulis* plants were found on hillsides. In the floodplain area, only one *S. acaulis* plant was found, which was much lower than the average number of plants found in the other sections of Transect 1. Plants were found in every section of Transect 2, which was raised above the floodplain, and no plants were found in Transect 3, which ran alongside the glacial runoff river, and was directly in the floodplain. All of this data points to soil moisture as a limiting factor for the presence of *S. acaulis*, which could potentially limit its use in tracking glacial retreat, particularly in areas of active melting and jökulhlaups.

### 5.2 Biotic Variables

There was no significant correlation found between diameter size and epiphyte load, which was the main biotic variable tested in this study. However, the fact that many of the plants had an epiphyte load is important because it violates one of the basic assumptions of cushion plant dating, namely that the plants being measured are growing under optimal conditions. The results for measurements of roundness and patchiness also violate the assumption of optimal growth conditions. Similar to the epiphyte load results, while there was not strong correlation between patchiness or roundness with diameter length, the fact that many of the plants were not round and/or patchy proves shows that they have not had optimal growth conditions. The violation of the optimal growth condition does not eliminate *S. acaulis* as a potential phytometer, however it does indicate the need for more information to be included in the growth curves.

### 5.3 Potential errors

Based on an effort to imitate the studies of Benedict (1989) and McCarthy (1992) this study had a low sample size and relatively weak statistical data. Using data from only the largest plants measured to test cushion plant diameter and substrate age relationships shrank the sample size from 207 plants to 37.

There may also be potential errors in the measurement of plant diameters, although the study only claims accuracy to the nearest cm. The surveying method could have also produced errors. A more complete surveying method should include detailed aerial photographs in order to ensure that all large plants are found and measured, rather than a scan of the area from the ground.
6. Conclusion

Until further study is done, *Silene acaulis* cannot be used an accurate proxy for substrata age. This study has confirmed many of the potential issues with using *S. acaulis* as a phytometric proxy and provided strong evidence that the growth curves of Benedict (1989) and McCarthy (1992) are inaccurate. It has shown that there are clearly abiotic and biotic variables affecting growth which have not been accounted for in growth rate curves. In addition, this study raises the issue of soil moisture in glacial forefields which might prevent the colonization of *S. acaulis*.

Despite the inaccuracy of Benedict (1989) and McCarthy’s (1992) growth curves, the usefulness of *S. acaulis* should not be dismissed. Even if it cannot be used as an accurate dating method, the results from Transect 1 show that there is potential to use it as an accurate relative dating method. However, this will only be possible if the variability in micro-environments can be quantified and included in the sampling method or data analysis, so as to minimize the effects of variable growth rates on measures of age.

As climate changes continue to rapidly change arctic regions, it is critical to gather as much data as possible in order to understand current changes, predict future changes, and adapt policy responses. Proxy dating techniques are often inexpensive, effective ways of extending records of change into areas that have not been monitored. However, there are very few proxy dating techniques available for recent changes in the Arctic. As correctly stated by le Roux and McGeoch (2004), cushion plants represent one of the best opportunities to extend proxy dating for recent changes into polar regions. Therefore further work should be done to enhance the accuracy of dates obtained from *Silene acaulis* in order to create a valid phytometric proxy for the Arctic region.


Frenot, Y., Gloaguen, J. C., Picot, G., Bougere, J., and Benjamin, D., 1993: Azorella selago Hook, used to estimate glacier fluctuations and climatic history in the Kerguelen Islands over the last two centuries. Oecologia, 95: 140-144.


Appendix 1

**Figure 1** – Boxplot of patchiness. Overlap between boxes shows no significant correlation between patchiness and diameter.

**Figure 2** – Boxplot of Epiphyte Load. Overlap between boxes shows no significant correlation between epiphyte load and diameter.

**Figure 3** – Linear regression of roundness versus diameter. Shows a slight positive correlation between roundness and diameter but with large variability. R-squared = 0.01, p-value < 0.01.
Figure 4 – Boxplot of patchiness. Overlap between boxes shows no significant correlation between patchiness and diameter.

Figure 5 – Boxplot of Epiphyte Load. Overlap between boxes shows no significant correlation between epiphyte load and diameter.

Figure 6 – Linear regression of roundness versus diameter. Shows a slight positive correlation between roundness and diameter but with large variability. $R^2 = 0.07$, p-value < 0.02.