Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Bachelor Thesis (Natural Sciences)

How do interanual differences in *Ranunculus pygmaeus* growth relate to climate ?

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Declaration of Originality

I hereby declare that the written work I have submitted entitled

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is original work which I alone have authored and which is written in my own words.[1]

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Contents

Preface

"Ne cueillez pas les fleurs, il pousserait des pierres"[2]

Samivel

I would like to introduce my Bachelor thesis with a quote that I find very beautiful and dear to my heart. Indeed, despite being once collected for their beauty, plants are now protected to preserve biodiversity. Some of these plants are in danger of disappearing if nothing is done to protect them. In order to understand their way of functioning, it is possible to analyze the past to understand their way of developing and protect them better. The sacrifice of collecting these plants in the past, nowadays finds justification in allowing us to understand the mechanisms of its growth.

Figure 1: Macun in the mist (Juillerat, Romain. Sept 2020)

[2]Don't pick the flowers, stones would grow

Abstract

Ranunculus pygmaeus is an alpine plant that is found exclusively in the canton of Graubünden in Switzerland. One population can be found in the region of Macun, and two others are located nearby. This glacial relict has a very narrow ecological niche and is today endangered: Global warming appears to have an important role to play. This is why it is needed to better understand the influence of climate on its morphological characteristics. This is what is explored in this thesis. With the help of statistical analysis, the relationship between the plant's traits and climate can be better understood. The results show that its growth is affected by meteorological factors such as temperature, snow or rain.

Figure 2: View from Macun (Juillerat, Romain. Sept 2020)

Acronyms and Abbreviations

ETH	Eidgenössische Technische Hochschule
WSL	Eidg. Forschungsanstalt für Wald, Schnee und Landschaft
SLF	WSL-Institut für Schnee- und Lawinenforschung SLF, Davos
SNP	Swiss National Parks, Graubünden
R. pygmaeus	*Ranunculus pygmaeus*
T. tenuifolia	*Tephroseris tenuifolia*
VH	Vegetative height
RH	Reproductive height
LL	Leaf length
LW	Leaf width
nL	Number of leafs
nI	Number of inflorescences

Chapter 1

Introduction

It is well known that climate change is of main concern nowadays: temperature and precipitations will be affected significantly. These changes will cause many problems, among others in the plant kingdom. Indeed, there are plants that have - over time - specialized and adapted to a certain environment (their ecological niche). The changing climatic conditions will disturb these ecosystems and the fragile equilibrium until now present may very well disappear: This will have grave consequences on plants. As a result, they could for instance migrate to a more favourable place, evolve or become extinct. Obviously, extinction is what we want the least, as it only adds to the current biodiversity loss observed around the world.

1.1 Effects of climate change on alpine plants

There are several meteorological variables that influence directly or indirectly the biology of alpine plants. For example: CO_2, temperature, nitrogen deposition, drought and snow depth (and the time of its melting)[1]. It is expected that an increase in CO_2 could improve the growth of alpine plants and thus allow them to reach their optimal height more quickly. However, their efficiency would remain unchanged[1].
The temperature variable does not influence every plant in the same way. Some plants that appreciate a warmer climate will see their occurrence or abundance increase. On the contrary, plants that are adapted to the cold will have decreasing occurrence or population sizes[1]. Temperature can also have an indirect effect. Indeed, a rise in temperature would make the forests move to higher elevation to take advantage of more tolerable climatic conditions. It would then add competition to the alpine plants by entering their habitat[2][3].
In addition, a warming of the alpine atmosphere and soil could increase biological and bacterial activity. This may result in a better yield of nitrogen decomposition and mineralization[4].
The increase in nitrogen due to anthropogenic activity - such as fertilizer and fossil fuels - could increase the biomass of alpine plants. Indeed, their growth is limited by the amount of nitrogen (and phosphor), so the increase of this element would impact the growth of the plant[5]. On the other hand, it is known [6] that a fertilized grassland contains less biodiversity due to too much competition from only a few dominant plants. The disruption in the proportion of nutrients could decrease the biodiversity of the plants. This consequence can be accentuated by a better yield of nitrogen decomposition and mineralization due to the increase of biological

[1] What has just been described is called thermophilisation

and bacterial activity caused by the warming of the alpine atmosphere and soil[4]
The consequences of a period of drought due to a lack of rain or snow in an alpine climate could be more dramatic than in a temperate climate. But we do not yet know how drought resistant the ecosystem is and how these alpine territories will react to a prolonged drought.
In addition to the fact that the plant will have to cope with physiological stress due to water deficiency, it will also be exposed to indirect side effects. These effects include a decrease in the solubility of nutrients, especially nitrogen, as well as a low self-cooling capacity of the plant (through evapotranspiration of the plant, heat can be dissipated)[7]. Concerning the snow variable, both the length and the depth of the snow cover are expected to decrease because of climate change, influencing the phenology, growth and reproduction of alpine plants[8].

Not all plants have the same requirements [9] for variables such as water resources or temperature[1]. A change in these parameters could therefore change the floral composition by advantaging some species and disadvantaging others. In this thesis I choose to treat the problem of *Ranunculus pygmaeus*, which, according to its current occurrences in moist snow beds, is in need of a lot of humidity[10] and thus could disappear if the climate dries up.

R. pygmaeus is a relict plant species in the European Alps that is likely to be particularly endangered by climate change, which could change key environmental parameters at the very restricted sites where the plant occurs and limit its propagation and growth. This work will demonstrate whether there is a correlation between certain morphological traits of *R. pygmaeus* (vegetative height, reproductive height, leaf width, leaf length, number of leaves and number of inflorescences) and some key meteorological variables affected by climate change (snow depth in the winter before the growing season, rainfall during the growing season, and average temperature during the growing season)[2]. In this work, the chosen morphological traits of herbaria samples of this plant will be measured and related to the meteorological conditions of the respective year in order to highlight the most favourable conditions for the growth and reproduction of *R. pygmaeus*.

1.2 Protective measures already in place

R. pygmaeus is a rare[11][12] plant of highest protection priority on the list of the national priority species for Switzerland[13]. It is threatened by climate change, which decreases the area of its potential habitat. In order to protect it, some measures have already been put in place: The creation of a protected area (such as the affiliation to the national park), the renunciation of tourist development, a regular inventory controls[14].

1.3 Research question and hypothesis

My work focuses on one main research question (see below). To elaborate the hypothesis related to this question, I looked at a wide range of research papers and literary works, which can be found in the bibliography.
Due to lack of time, I had to abandon another idea related to priority species in the Swiss National Park that came to my mind. Its details can be found in the chapter Prospect 6.1 and maybe be elaborated for another bachelor or masters thesis.

[2]Several meteorological variables have been put forward in this introduction, but only these three could be considered in this thesis

1.3.1 Research question

What is the sensitivity of *R. pygmaeus* to certain meteorological variables such as temperature, quantity of rain or quantity of snow? How will the different morphological traits of *R. pygmaeus* (vegetative height, reproductive height, leaf width, leaf length, number of leaves and number of inflorescences) react in the face of climate change?

1.3.2 Hypothesis

High humidity, the summer heat and long-lasting snow are optimal conditions for *R. pygmaeus*. The hypothesis is thus the following: The higher these weather variables (temperature, rain and snow) are during a year, the better the plant will do. Whether a plant does well or not will be represented by its growth traits: the plant will be larger and have more leaves and inflorescences in years with favourable climatic conditions.

1.4 Definitions

Some important definitions are listed below.

Priority species are plants that require special attention in regard to conservation in Switzerland. They are classified on a scale of 1 (highest) to 4 (lowest priority). The level is determined due to a combination of the national level of endangerment and the responsibility that Switzerland carries for the overall, international persistence of a species [13]. This is why a species can be a priority in Switzerland because of its rarity, but extremely frequent in other regions of the world where the climatic conditions are more suitable (e.g. *R. pygmaeus* in Scandinavia)[12][11].

Endemic species, as opposed to a cosmopolitan plant[3], can only be observed in one or a few places on the globe. An endemic species is therefore geographically limited in a small area of a larger region. Variables that prevent the spread of the species are a lack of appropriate conditions related to soil, moisture, snow cover, or temperature, or the impossibility of reaching a site that would be as suitable as the previous one. A large number of endemic species at one location may be the consequence of a rich variability of habitats (hills, steeps slopes or sun variation)[15]. The formation of an endemic species often occurs during a prolonged isolation of a place. This term can be clarified by speaking of relict species[16].

Relict species are species that are found only in very specific habitats (Endemism), but were previously very widespread. Following an environmental perturbation event (such as an ice age), it has been able to survive only in specific places (e.g. without competition). In due course it had difficulty to propagate again and therefore remains in this specific place[17].

An ecological niche is the ensemble of tolerance's characteristics of the needs of a living being[18]. There are two types of ecological niches. The fundamental niche (Hutchinsonian niche), which does not take into account competition and is based only on physiological characteristics, and the realized niche, which does take into account competition and is determined by socio-ecological variables. The fundamental niche is greater than or equal to the realized niche[9].

[3]That can be found anywhere in the world

Snow bed is a place where snow accumulates in winter and stays sheltered from high temperatures in summer, so that the snow lasts for many months. Often behind a rock or in a depression, this place offers moisture-appreciating plants (like *R. pygmaeus*) a high soil humidity. The vegetation period is however limited because of the snow accumulation[19].

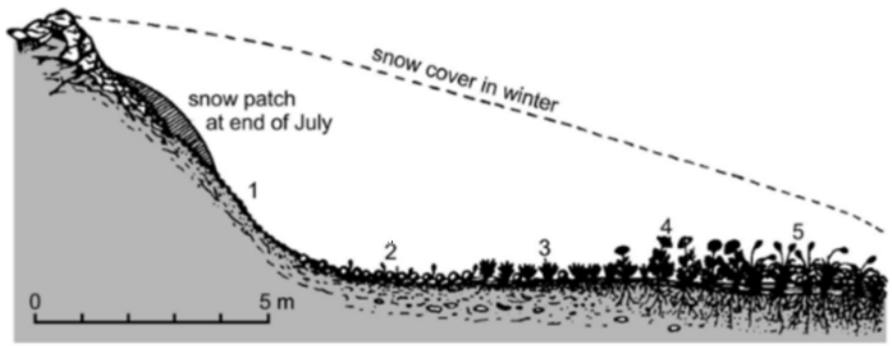

Figure 1.1: Illustration of the creation and vegetation of a "snow bed". In winter, a deep layer of snow accumulates in a depression or at the lee side of an obstacle, in summer the snow melts except in some places where shade is often present. Depending on the length of the snow-free period, different particular vegetation types form. 1 *Polytrichetum sexangularis* (community that includes *R. pygmaeus*), 2 typical *Salicetum herbaceae*, 3 formation with *Gnaphalium supinum*, 4 formation with *Ligusticum mutellina*, 5 *Caricetum curvulae*[20]

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Hydrological Year[4]: A 12-month time span that begins after the usual month of a short water period. Hydrological years in Switzerland start in November, hydrological winters last between November and April[21].

1.5 Goal of the thesis

The main goal of my thesis is to highlight the effects of meteorological variables on the morphological characteristics of *R. pygmaeus*. The indirect goal of this thesis would be to inspire others to do similar studies (perhaps in extended ways) on other plants to broaden the range of studies and find solutions to preserve the vegetation against climate change. These beautiful plants are part of the environment and contribute to its biodiversity. Their loss would be devastating.

[4] I only use this definition for the data analysis

Chapter 2

Methods

As previously announced, the purpose of this work is to correlate meteorological variables with morphological changes in *Ranunculus pygmaeus*. To do this, I used pictures of herbarium specimens of *R. pygmaeus* collected between 1898 and 1978. Using the software `ImageJ` [22], I was able to measure the different morphological traits of these specimen. I collected the meteorological data I needed (temperature and precipitation) from `MeteoSwiss`[23], and correlated them with the different morphological traits measured, using `R` [24]. These correlations between morphological traits and meteorological data serve as a reference point to estimate the climatic preferences of the plant.

I will first describe the area where the plants were found, then the plant itself and its morphological traits that have been correlated with the meteorological data. Finally I will enumarate the meteorological data that comes from the `MeteoSwiss` website.

2.1 Area description of Macun

The protected area of Macun[1] is a high plateau with block glaciers and more than 20 mountain lakes of various sizes. This region, which owes its name to Piz Macun (2889m), is located in Switzerland, in the canton of Graubünden. More precisely in the inner-alpine valley called the lower Engadine. Macun is a glacial cirque at the end of the Zernina valley (branching off the Engadine towards the south at Lavin) and is at an altitude between 2600m and 3050m. On this plateau, sometimes flat (wet) and sometimes hilly (dry), it is common to come across ibexes[2]. These variations in topography also allow the formation of "snow beds"(see 1.4). In contrast to to the rest of the Swiss National Park, which is on the Engadine Dolomites, Macun is on the Silvretta geological layer. The rocks are therefore of a crystalline, metamorphic type (gneiss, serpentinite and amphibolite). Concerning the weather, the average temperature in this area is about -2°C and it can rain more than 1600mm (especially in June to August and October to November)[25][10][26](fig: 2.1).

Macun has an average of only 18 species per 20m^2. This relatively low number is due to several variables including altitude and substrate type. Macun is located on siliceous soil due to its crystalline bedrock[27]. The pH of this terrain is therefore lower and reduces the probability of finding different taxa by about 16%. Indeed,

[1]Macun has been part of the Swiss National Park (SNP) since 2000

[2]Macun means ibex in Vallader dialect, which is a form of Romansh language spoken in the Lower Engadine valley

92% of the taxa grows well on calcareous soils while only 76% on siliceous soils[28]. This 16% decrease can be explained by the difficulty that plants have to absorb micronutrients when soil pH is low[3][29]. Altitude, or rather the variables influenced by altitude (temperature, snow cover, strong winds, heavy precipitation, decrease of partial pressure of oxygen and CO_2) will lead to create unfavourable habitat for more species and thus decrease the number of species per m^2[30]. A doctoral thesis also showed that the two main variables influencing the decrease in species richness were daily temperature and soil pH[31]. The master thesis of Bogdan Favre and Wanda Wietlisbach[10] showed that two species were strongly represented in Macun: *Salix herbacea* and *Carex curvula*. During my excursion on this plateau I could also observe other plants, such as *Sesleria caerulea*, *Saxifragales*, *Achillea erba-rotta* and of course *R. pygmaeus*, which take advantage of this varied terrain with its different micro-habitats.

Figure 2.1: Picture of the area in Macun (Juillerat, Romain. Sept 2020)

2.2 Plant description

R. pygmaeus can be found in the lower Engadine (1700-2400m) on low-calcareous amphibolite and mica schist soil. It is present in avalanche corridors, on the morainic slopes of moss-rich snow patches called snow beds[4]. Snow beds create a good microclimate for *R. pygmaeus* by offering a winter protection and a shorter vegetative period. They allow *R. pygmaeus* to have a competitive advantage against other species[26][32].

R. pygmaeus is a relatively small perennial plant with short rhizomes[5]. It measures only between 1 and 7 cm in height. Its hairless leaves are basal palmatilobated and

[3]pH of 4.5 is the mean for Macun

[4]No more than two months without snow (see :1.4)

[5]The underground stem

composed of 3 or 5 lobes. It only has one yellow, slightly hairy flower per stem, which has a diameter smaller than 1 cm. The flower appears after the snow starts melting. There is a possible confusion with *Alchemilla alpina* when both plants are young because of similar leaves. But as soon as the leaves of both are developed, the difference is obvious since the rosette leaves of *A. alpina* is toothed at the end of its lobes[14].

Figure 2.2: R. pygmaeus (Juillerat, Romain. Sept 2020)

As previously mentioned, *R. pygmaeus* is a species that has a strong dependence on places with snow bed and high moisture values in summer. It is feared that, if the growing season becomes longer and drier due to global warming, this could create increased competition by other species that previously could not grow in these highly specialized habitats, which then would outcompete *R. pygmaeus*[10].

In the rest of the world, this plant species is found in quantity in the northern hemisphere: In the central alpine area (on silicate and mica schist), in arctic Europe, on Scandinavian islands, in Siberia, in the Himalayas or even in arctic America and Greenland[33][34][35][12][11].

2.3 Herbarium

2.3.1 Morphological traits

The characteristics of the plant being stated, I will now highlight the morphological traits used for the analysis. These are features that are easy to measure from a picture of specimens found in the herbarium. The following morphological traits are tested for the influence of meteorological variables:

Figure 2.3: Example of a picture of a herbarium specimen

- *Vegetative height (VH)* : From the top of the root to the longest leaf.
- *Reproductive height (RH)* : The length of the stalk from the top of the roots to the base of the inflorescence.
- *Leaf length (LL)* : The longest distance of the largest leaf.
- *Leaf width (LW)* : The widest distance of the largest leaf.
- *Number of leaves (nL).*
- *Number of inflorescences (nI).*

2.3.2 Treatment of morphological data

In order to have access to the growth characteristics of the plant over a number of years, I made requests to many Herbariums in Switzerland. If *R. pygmaeus* was listed (which was often the case), they sent me pictures of the different herbarium records. All Swiss herbarium specimens were collected from the population of Macun, which was discovered at the end of the 19th century and, for a long time, was the only known population in Switzerland. At earlier times, many passionate collectors probably wanted to have this species in their herbarium collection. It is thanks to these collectors that I was able to get a total of 26 photographed documents including approx. 200 individual specimens of *R. pygmaeus*. These had been collected between July and August over a time span of 80 years, representing 14 different years.
I arbitrarily decided that the group of plants picked on the same day by the same picker would represent a "record", regardless of whether the plants came from the same collection sheet. This is due to the fact that the collector plays a role in the choice of the plants harvested. My data are thus composed of 17 different "records". It was more important to have a high number of "records" of different years rather than a total number of copies, because, within a "record", the data is not independent (same place and same person). Plants are thus potentially more similar than expected by chance within the same "record".
I did not measure each individual specimen on the sheets, but selected a subsample. In order to not introduce a bias by selecting the specimens in a non-random way, I created a small algorithm on `Python` [36] that indicated which plants to measure. The more plants on the picture, the more to be measured (30% of the total specimens on the picture, or at least 3 if it was possible). If the morphological traits were impossible to measure (e.g. because a specimen was damaged or leaves folded over during the herbarization process), I took the next number in the list. All morphological traits detailed above were measured using `ImageJ`. Because of the large difference of individuals within one "record", I decided to average the measured values of the morphological traits within one "record". I analyzed the relationship of those averaged values with the meteorological data that is described below.

2.4 Meteorological data

The meteorological data were measured in Samedan, the nearest (about 30km as the crow flies) weather station that was in operation when the first specimens of my analysis were collected. Indeed, the station has collected temperature (°C) and precipitation (mm) data since 1864. Despite the high probability that the microclimates are different between Macun and Samedan, the meteorological station in Samedan gives us an indication of how the weather differs from one year to another. These monthly averaged data from the `MeteoSwiss` website were downloaded on January 15, 2021 from the `IDAWEB` database [37].

In order to analyze the relationship between morphological traits and meteorological variables, I considered three parameters. Firstly, the average temperature during the growing season (June-July), which is an important determinant of plant growth in general. Secondly, the amount of snowfall[6] during winter (from November to April) before the plants were collected (July or August), which gives us an indication on the annual depth of the snow beds that provides the humidity needed by

[6] As I stated in the chapter 2.2 on plant description, *R.pygmaeus* grows exclusively in snow beds which constitute its ecological niche, so I assumed that this is an important variables to consider in terms of the influence of climate on the plant's morphological traits

the plant in early summer. Finally, the amount of rain during the vegetative period (June-July), as growth of the plant may also be restricted by summer drought[38]. The temperature that I chose was the monthly mean temperature of June and July (the vegetative period before collection of the specimens). I therefore averaged this monthly temperature in order to get one value of temperature per year. Since local snow measurements are not available, I assumed that the precipitation that fell between November and April was snow. Precipitation that fell later (June-July) was assumed to be rain. I therefore distinguish the "precipitation" variable into two separate meteorological variables (snow and rain). It was important to separate these two types of precipitation because they influence the plant in different ways (see: 1.1). I therefore first had to convert the "years" of each measure to "hydrological years"(see: 1.4) in order to simplify the data analysis. The precipitation of the hydrological winter was thus assumed to be snow. The sum of this precipitation was considered as a proxy for the amount of snow accumulating over the winter before the specimens were collected. Secondly, I summed up these two months as a measure for summer precipitation (see assumption above) for each year when specimens were collected.

2.5 Description of the statistical analysis

For the statistical analysis, I used `R`, and `Excel` [39] for data processing. After having done the work described in the previous chapters (measurements and averages), all morphological trait data were visually checked if they were normally distributed (with the function `hist()`). Logarithmic transformation was needed in order to have normally distributed residuals.
I then created linear mixed models (with the function lm()) to analyze how each of the six measured morphological traits was influenced by the three meteorological variables and their interactions. To choose the best model, I did a backward elimination with p-values using the function `step()` to remove the meteorological variables that did not explain variation in the model. To finish, I summarized the model with the function `summary()`and I made a plot of each model to interpret how morphological traits of the plants were influenced by the meteorological variables. For the visual interpretation of interactive effects, I categorized both rain and snow data each into two categories. Snow is separated into low and high snow levels ($<$ 220mm in the hydrological winter being low and ≥ 220 being high). Regarding the rain, below 135mm in June/July is defined as low rain level, and above as much rain level[40].

Chapter 3

Results

In the following table 3.1 the different trends in morphological traits are summarized as a function of the different meteorological variables (temperature, snow and rain) are summarized. The arrows show the trends, if there was no significant effect (p-value >0.05) no arrow were ploted. The stars show the degree of significance.
The temperature seemed to have a positive influence on each plant's morphological trait. With higher temperatures, the plants grew larger VH ($p=0.0006$), RH ($p=0.010$), LL ($p=0.042$)) and had more leaves ($p=0.047$). The amount of snow in the winter before the growing season seemed to decrease the growth of the vegetative height ($p=0.001$). It also slightly (the slope on the graph is only slightly inclined) decreased the reproductive height ($p=0.028$). The amount of snow decreased the number of leaves slightly as well ($p=0.041$). The amount of rain during the growing season had little effect on the plant's morphological traits. It decreased the vegetative height ($p=0.028$) and showed no impact on the leaf width ($p=0.040$). In many cases, I found interactive effects between the meteorological variables in influencing plant morphological traits. The vegetative height tended to decrease with more snow ($p=0.001$), but more drastically if there was more rain in the growing season ($p=0.024$). If the amount of snow was relatively low, high temperatures increased the vegetative ($p=0.0009$) and reproductive height ($P=0.030$) and the number of leaves ($p=0.048$). If the snow layer was too high, the tendency rather showed the opposite (decrease of vegetative height and number of leaves, but a slight increase of the reproductive height). If there was enough rain, an increase of the temperature had a positive impact on the leaf width ($p=0.036$).
The influence of meteorological variables on the number of inflorescences is not significant. In the following table, I do not show any trend because the p-value is too high (>0.05).

Variable	VH	RH	LW
Temperature	↗***	↗*	
Snow	↘**	(↘)*	
Rain	↘*		⟶*
Snow:Rain	↘ if MR;(↘) if LR *		
Temperature:Snow	↘if MS;(↗)if LS***	(↗)if MS;↗if LS*	
Temperature:Rain			↗ if MR; ↘ if LR *
Variable	**LL**	**nL**	**nI**
Temperature	↗*	↗*	
Snow		(↘)*	
Rain			
Snow:Rain			
Temperature:Snow		↘ if MS;↗ if LS	
Temperature:Rain			

Table 3.1: **Summary Table of Trends**: This table shows the relationships between the different morphological traits analyzed (VH, RH, LW, LL, nL, nI) and the meteorological data and their interactions (indicated by ":"). ↗ means "an increase in the morphological trait if the meteorological variable increases". ↘ means "a decrease in the morphological trait if the meteorological variable increases". ⟶ means "no change in the line if the meteorological variable increases. "( )" means "slightly". (Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1). Abbreviation: Much snow (MS), much rain (MR), little snow (LS) and little rain (LR). Original plots can be found in the appendix

The trends highlighted in the previous table are from the plots in the Appendix A.2. The following plots are the most important ones. The plots also show the confidence intervals. These are rather large in all of the plots, emphasizing that there is a lot of unexplained variance in the data. That can also be seen by looking at the adjusted R-squared A.2. The closer to 1, the better the variability in traits is explained by the variables included. My results show mostly small adjusted R-squared: 0.3999 for VH, 0.2193 for RH, 0.2706 for LW, 0.1506 for LL, 0.0298 for nL and -0.0005 for nI. These adjusted R-squared indicate a low probability that the trait values are exclusively explained by the meteorological variables.

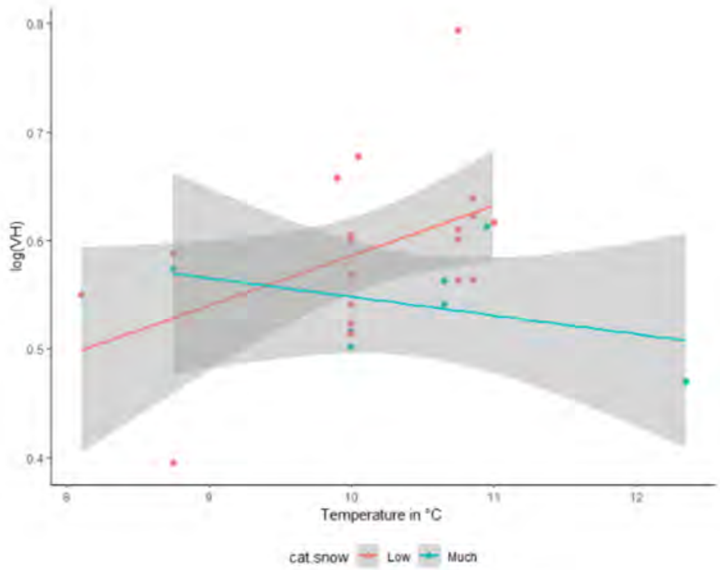

Figure 3.1: Relation between temperature, snow quantity and vegetative height (VH)

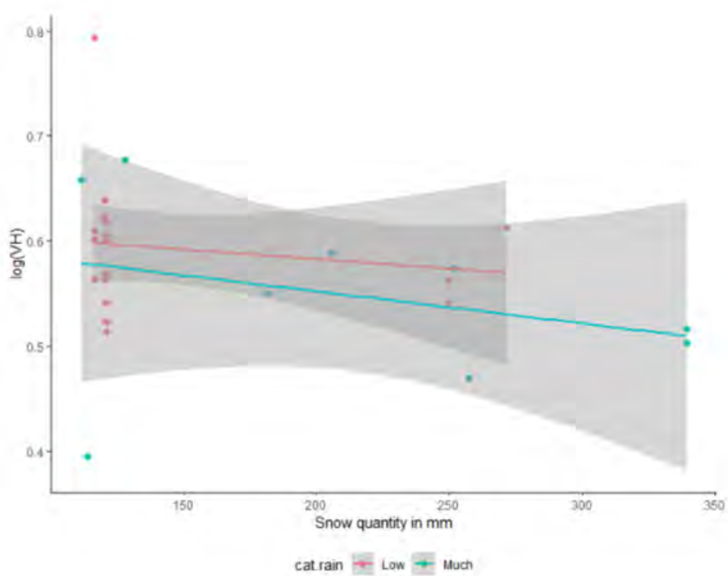

Figure 3.2: Relation between snow, rain quantity and vegetative height (VH)

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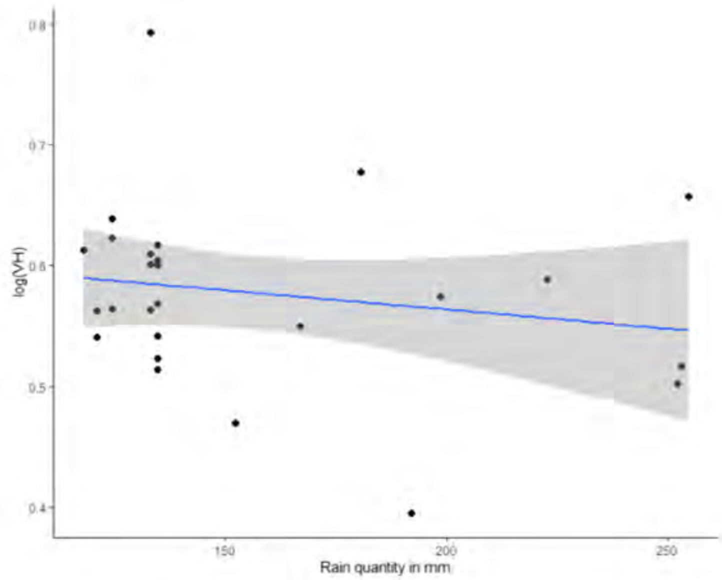

Figure 3.3: Relation between rain and vegetative height (VH)

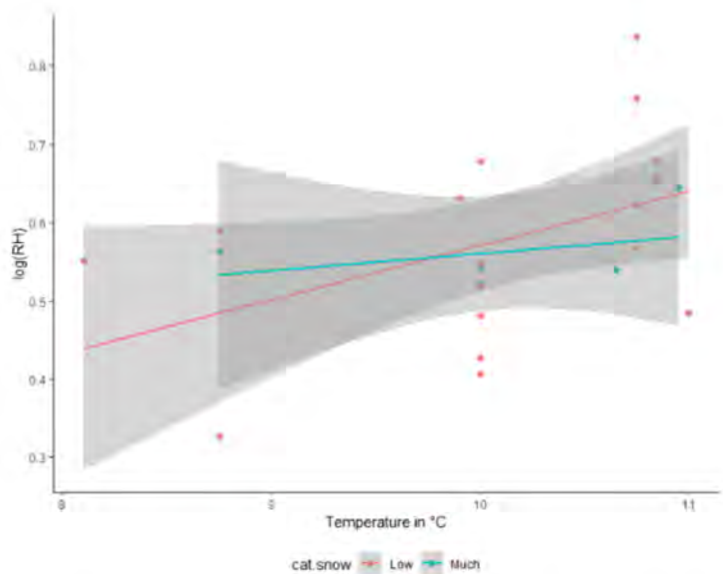

Figure 3.4: Relation between temperature, snow quantity and reproductive height (RH)

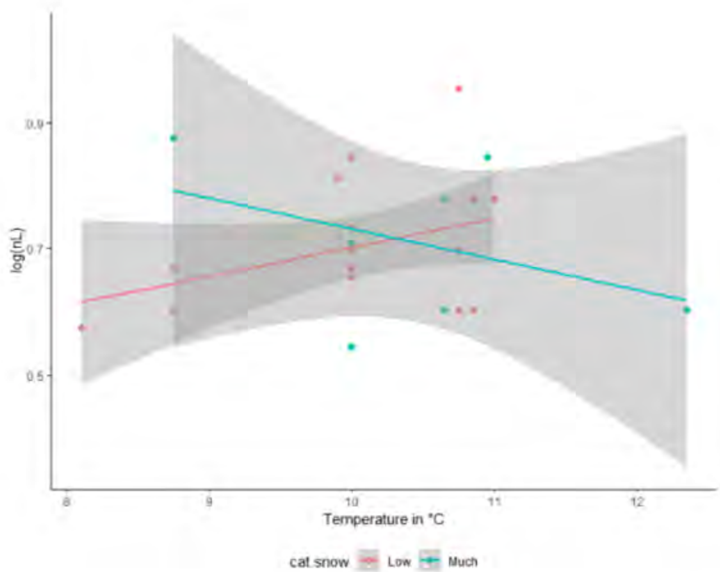

Figure 3.5: Relation between snow, rain quantity and number of leaves (nL)

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Chapter 4

Discussion

My hypothesis was that the higher the temperature, the rain and the snow quantity were during a year, the better *Ranunculus pygmaeus* would do. This would be represented by its growth traits collected from herbarium specimens: the plant would be larger and have more leaves and inflorescences in years with favourable climatic conditions.
In the following I will first interpret my results and explain why my study is interesting, then state the limitations of my study.

4.1 Interpretation of the results

The results obtained in a simple linear regression did not confirm all of my hypotheses as previously mentioned, but remain consistent. They should be interpreted with care due to the low adjusted R-squared which indicate small likelihood that the variability of the *R. pygmaeus* growth traits are explained by the meteorological variables alone.
The results regarding the impact of temperature on the morphological traits were as expected: the analysed plants were generally larger with more leaves and inflorescences when the temperatures were high. This was predictable because the plants generally grew better with higher summer temperatures. On the other hand, the results for snow cover were not always as expected. High snow levels seemed to decrease the size of the plant (and the other morphological features), which is the opposite of what my knowledge of the ecological niche suggested. Indeed, snow creates a particular ecological niche by humidifying the soil to reduce competition against *R. pygmaeus*. Snow naturally still plays a role, but only when it is not present in too high quantities - with an extremely deep snow cover, the snowmelt would occur much later in the season that the growing period could be reduced beyond what *R. pygmaeus* needs for sufficient growth and reproduction. Thus there could be a threshold: warm summer temperatures with a medium layer of snow helps the plant to grow. With too much snow, even warm summer temperatures do not foster growth anymore. In spite of the high moisture resistance of the plant, water excess from late-melting snow could also decrease the size of the plant. On the other hand, if the plant is exposed to high temperatures after a snow-poor year, water may be limiting and it is then preferable for the plant to have a year richer in rain to avoid the ground being too dry.
These results may show the trade-off between a preference for high temperatures and thick snow layers. It seems that the plant is leaning towards a preference for high temperatures. This may be preferable given the decrease in annual snowfall. A lack of snow has less impact than a lack of warmth.

Nevertheless, a constant decrease in humidity is undoubtedly very unfavorable to this plant which likes humid places. As long as the temperature increases, and that the humidity is sufficient for the plant, it should have its growing requirements met (as the data say). But as soon as the conditions in Macun change, the niche of *R. pygmaeus* will be disturbed and it might not be able to last any more. Global warming could therefore have very harmful effects on this plant which could then disappear. If this is the case, an anthropogenic transplant could be implemented.
Of course, the interpretation of growth patterns does not give any indication on the abundance of plants and the population persistence. It is assumed that a year rich in snow will allow limited growth of a high number of *R. pygmaeus* plants, therefore a high proportion of *R. pygmaeus*. A warm year, on the other hand, would have large *R. pygmaeus* in small numbers. The proportion of *R. pygmaeus* compared to other plants would be lower.
My study rather gives an idea about the fundamental niche. However, this does not take into account the biotic interactions with other species, i.e. with potential competitors, which is called the realized niche (the difference between fundamental and realized is explained in the chapter 1.4). When temperatures fluctuate, I then see these year to year variations. When however at some point there is always higher temperatures, then other species will also be able to grow in the habitats previously only home to a few specialists. These will not be very competitive given their very small size (even if there is some plasticity in the size), and there might be longer-term replacement of specialists by generalists.

Concerning the results of adjusted R-squared that indicate a low probability that the variability in growth traits are exclusively explained by the meteorological variables, there are several possible reasons. First, it is possible that the most influential variables were not taken into account. For example, it could theoretically be that soil nitrogen has more importance than the used weather variables, but it is impossible to measure this now. Secondly, it could also be that the weather variables analyzed were the correct ones, but with a poor approximation due to the distance and the low resolution (monthly averages) of the weather measurements. It might have been better to use more precise variables such as Macun soil temperature or the date of snowmelt to a better relationship of these meteorological variables with plant growth, however, such data is not available for the late 19th and early 20th century.

Other studies with similar methods and goals to mine have been conducted. Often they show that the morphological traits of the plants studied are correlated with the meteorological variables[41][42], but sometimes no correlation is highlighted[43]. Compared to other studies that take into account many different species, my study has the following advantage: It focuses on a single population. It is therefore easier to control for genetic differences within the population.
In spite of the good functioning of such a study, mine, which consists in measuring plant morphological traits on herbarium, is only rarely used. This type of study works very well and is really easy to conduct, but is underrated[44]. Nevertheless, it also has weaknesses, and there could be influencing factors that could not be accounted for. These are described in the following section.

4.2 Limits of the study

Several limitations that could decrease the significance of the results can be enumerated. The following paragraphs describe the limits of my thesis.
Firstly, although I contacted a large number of herbaria and found a considerable number of records from the one population of Macun, the number of years with records is still rather low. Which leads to a limited statistical power. Moreover, the limited number of plant specimens was problematic in order to define the average size of the different morphological traits. I sometimes had to define an average with only two measurements which is not totally statistically correct. In order to improve this study, I could have invested more time in the research of herbaria in order to perhaps find more records. This way I would have had more plants to analyze. Nevertheless, Dr. Sonja Wipf and I searched for a long time all the places where herbaria could be found. We even checked foreign ones (Montpellier, where Braun-Blanquet lived) but the analyzed herbaria specimens are the only ones found. It could therefore be difficult to find more data.
Moreover, measurements from pictures are not easy to do. The quality of the image was not always as good as it needed to be, so especially the delineation between stem and root system was often difficult to make. This lead lead to a lack of precision. The leaves were sometimes folded or overlapped, which made a good recognition of the number of leaves difficult. It would have been easier to measure plant morphological traits from herbarium records in person. One way to improve this would have been to measure the different morphological traits of the plant in person. For that I would have had to go to the places where the plants were stored, which was not recommendable under the particular circumstances of the winter 2020/2021.
The collectors could introduce an unknown bias to the data. Do records contain big plants because of the environmental variables that let them grow optimally in that year, or because the collector specifically picked large specimens? As large plants are more visible, it is certainly a factor that is not to be neglected. This problem has been partially solved by averaging each "records". Also, in my opinion, this limitation is not very relevant because the "records" looked rather heterogeneous with respect to the plant morphological traits (personal intuition). Moreover it is very likely that the collectors wanted to collect all growth stages of the plant. Often, herbaria specimens were used as reference plants to compare them with other plants, not necessarily as "trophies" of particularly large or beautiful specimens.
In addition, the plants were collected over a span of several weeks in July or August. The August specimens had more time to grow, or to be damaged before being picked, an effect that cannot be excluded. With more "records" I could have statistically tested the effect of this temporal variable.
The meteorological data is not perfectly accurate. It comes from the nearest weather station to Macun that collected data since the sampling of the first specimens analyzed there. But at about 30km as the crow flies, it is far enough to lose accuracy, as the weather between upper and lower Engadina could be different. Also, data was available only at the resolution of one month. I had to estimate snowfall based on precipitation (snow or rain). The amount of snow in Samedan is certainly not the same as in Macun. The temperature as well as the amount of rain is not the same either. However, as I used these values only in a relative, not absolute sense to describe year-to-year variability, they can still give an idea of the type of year that took place.
Still concerning the meteorological data, it is difficult to clearly split the effect of summer temperatures and summer rain, as wet years were also cooler than dry years, i.e. there is a correlation between these two meteorological variables. The morphological traits showed however a clearer positive correlation with temperature, thus this seems to be the more decisive meteorological variable.

Snowfall gives us an idea of the amount of snow, which in turn is negative correlated with the vegetation period of the plant, but it would have been very appreciable to have the date when the snow melted as a variable, as the length of the growing season certainly would be a decisive variable. However, as there is no such data from such a long time ago, the amount of snow had to serve as a proxy (assuming that much precipitation in winter would result in a late snowmelt and vice versa). Finally, there are further morphological traits that would be very interesting, but not all the variables that come into play were taken into account. One potentially interesting trait would be the allocation variable (where in the plant organs resources are allocated to according to soil or weather conditions[9]). I only measured traits above ground, but it could be that environmental changes strongly affect traits below ground and therefore useful to measure them as well.

Chapter 5

Conclusion

This study has shown that the response of *Ranunculus pygmaeus*'s morphological traits are significantly related to meteorological variables. The more favourable the conditions are, the more pronounced the plant's morphological traits will be. Higher temperature tend to increase the size of the morphological traits and the number of leaves, whereas the amount of snow and rain decreases those features. We can relate these results to the changes that will occur the following years or decades due to climate change. From a purely analytic point of view, the plant will persist because there is an increase in temperature and a decrease in snow. However, once the duration of the growing period is long enough to enable other, taller species to grow in the same sites as *R. pygmaeus*, it is likely that this small species will be outcompeted. But there are still some questions to answer. How will the plant react to its new environmental conditions? What are the impacts of competition on such a fragile plant with a narrow niche? Unfortunately, these questions could not be answered in this work. Yet these could be the subject of another thesis in relation to further population development over the nearer past to actual climate measurements at the site of Macun.

Chapter 6

Prospect

This chapter is intended for ideas and analytical reflections. Due to the lack of time, not all analytical ideas have seen the light of day in this work. It is not impossible that an extension of this work will emerge, but for the moment it remains open.
In the following, I would like to also describe ideas for a project on the change in local population distribution of *Ranunculus pygmaeus* on Macun over the past 25 years. In the initial phase of my Bachelor thesis I made first steps towards such a project, but it became clear quickly that I could not follow up on both the topics above, as well as this one. Please note that in the initial phase of my work I have not only mapped *R. pygmaeus*, but also *Tephroseris tenuifolia* in and adjacent to the Swiss National Park. Information on *T. tenuifolia* can be found in the appendix and the methodology presented below would have applied to both species.

6.1 Comparison of the *R. pygmaeus* population in 1994 and 2020

The idea would have been to see the evolution of a small population, on a small scale, over a period of 26 years.

6.1.1 Research questions

How are individuals distributed, what variables influence this propagation and will climate change have an impact on propagation? Will it be favorable or on the contrary will plants lose ground in the face of the changes to come?

6.1.2 Hypothesis

Climate change will have negative impacts on *R. pygmaeus*. Climate change is expected to reduce the snow beds in the mountains. However, *R. pygmaeus* needs snow to become established. Its potential habitats will as a result decrease as well as the population.

6.1.3 Methods

To accomplish this study, several methods, using `Q GIS` [45], would have been used:

- A georeferencing of the locations of the old[1] and new mapping[2].
- An overlay of different maps, such as geological, NDVI (Normalized difference vegetation index) or snow cover, and climate layers reduced to 25m.
- A computation of the SDMs (species envelop models), i.e. the environmental conditions in which the species is found.
- An extrapolation of the environmental conditions for the future and predict where the species might still be present in the future.
- A model of the population distribution along climatic gradients, and a forecast of the evolution of this population using climatic prognostic maps made by WSL.

6.1.4 Status and expected outcome

So far, very little time has been invested in this study. Only a mapping of the plant has been done on the areas describes in the appendix A.1.2. The morphological traits of the plant have not been measured. The t tenui like the r pymg needs a relatively humid soil, so I think that the meteorological impacts will have similar effects on both plants. In the short term the plant could see its morphological traits grow thanks to the increase in temperature, but would risk disappearing because the soil would lose the humidity it needs.

[1]Reconstruction of the data collected in 1994 by Aita Rauch in an unpublished student work
[2]The collected data in July and September 2020

Chapter 7

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Appendix A

Appendix

A.1 *Tephroseris tenuifolia*

A.1.1 Plant description

Tephroseris tenuifolia can measure up to 80 cm high, it is an almost glabrous or white felted white that grows between June and August. Its stem is straight, strong, leafy, and stalkless except for the branches of its head. Its basal leaves measure up to 15 cm long. They are ovate and suddenly narrowing into a long stem. The plant has stalkless stem leaves with a narrowed or rounded base as well as flower heads of 3-4 cm broad, laid out like umbels on 3-15 rows. It has elliptic yellow ligulate flowers with their tongue-shaped part being approximately as long as the involucre. The involucre is without an outer envelope and bell-shaped, about 1 cm long. There are 15 to 23 involucral bracts in a row with felted, green or purple tipped hairs. The armpits of 2.5 to 3.5 mm have 10 to 12 longitudinal ribs and short hairs. The pappus hairs are in a row, yellowish white, rough[46]. *T. tenuifolia* can however be confused with the following plants: *Tephroseris ovirensis*, *Tephroseris salisburgensis* and *Tephroseris balbisii*. It can be found in humid, subalpine and nutrient-rich environments. The soil should preferably be calcareous, humic, clayey to silty. This is why it is present in the Graubünden and in Valsesia[33][47].

Figure A.1: *T. tenuifolia* (Juillerat, Romain. Sept 2020)

A.1.2 Aeras descritpion

Alp Chachen

On the top, the area is very much in demand for livestock and therefore strewn with excrement, which makes the soil rich in nutrients and conducive to *T. tenuifolia* (chapter: A.1.1). It is not very steep and relatively humid. At the bottom of the area, *Juniperus communis* colonize where *T. tenuifolia* seem to enjoy hiding.

Muschaun

This parcel is on the southern side of the valley. It is relatively sloping and steep, but flattened before joining the torrent. In spite of the humidity of the torrent, Edelweiss or *Dianthus superbus* (species preferring dry land[33]) can be observed here. This is probably due to the exposure of the soil to the sun, which dries out the land.

Figure A.2: Picture of the area in Muschaun (Juillerat, Romain. Sept 2020)

Val Mela

Bordered by a torrent, it is a area in a valley with little difference in level. This plot is very bushy and contains many *Aconitum napellus* which have almost all colonized it.

Figure A.3: Picture of the area in Val mela (Juillerat, Romain. Sept 2020)

Charnels

The plot is relatively sloping with flatter areas. Sometimes open, sometimes covered with *Pinus mugo* or other ground vegetation, the plot offers a multitude of possible habitats. It is not impossible to see *Paris quadrifolia* which is a plant that has climate and soil factors around 3[33].

Figure A.4: Picture of the area in Charnels (Juillerat, Romain. Sept 2020)

A.2 Tables and plots described in chapter results

A.2.1 Vegetative height

Here are the outputs of R concerning the vegetative height.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-2.0599	0.6618	-3.11	0.0055
VH$Snow	0.0122	0.0032	3.77	0.0012
VH$Rain	0.0020	0.0008	2.36	0.0283
VH$Temp	0.2307	0.0562	4.10	0.0006
VH$Snow:VH$Rain	-0.0000	0.0000	-2.45	0.0235
VH$Snow:VH$Temp	-0.0011	0.0003	-3.89	0.0009

Residual standard error: 0.05806 on 20 degrees of freedom
Multiple R-squared: 0.5199, Adjusted R-squared: 0.3999
F-statistic: 4.332 on 5 and 20 DF, p-value: 0.00782

Table A.1: Influences of variable on vegetative height

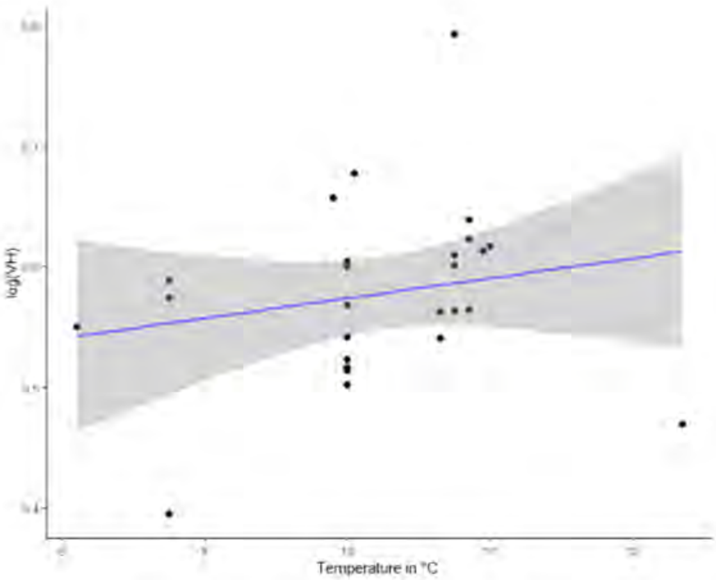

Figure A.5: Relation between temperature and vegetative high

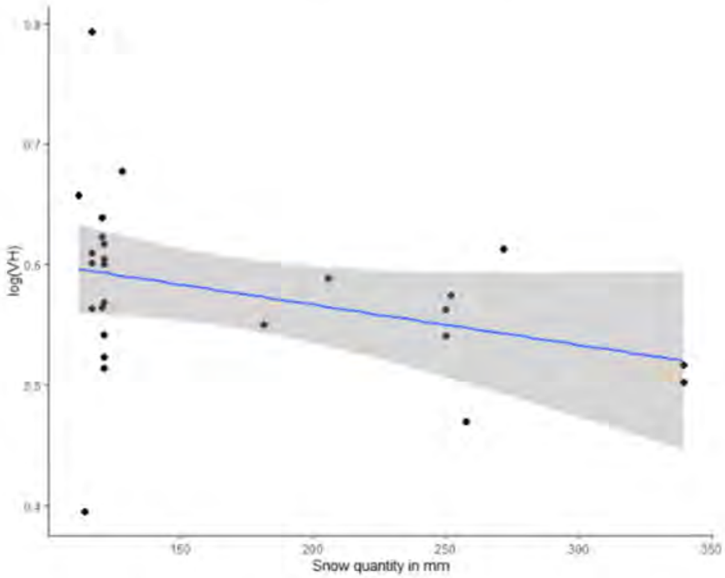

Figure A.6: Relation between snow and vegetative high

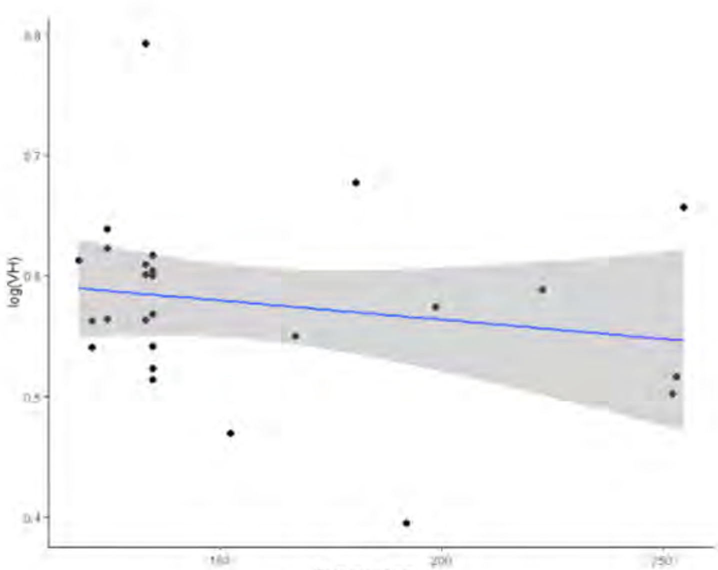

Figure A.7: Relation between rain and vegetative high

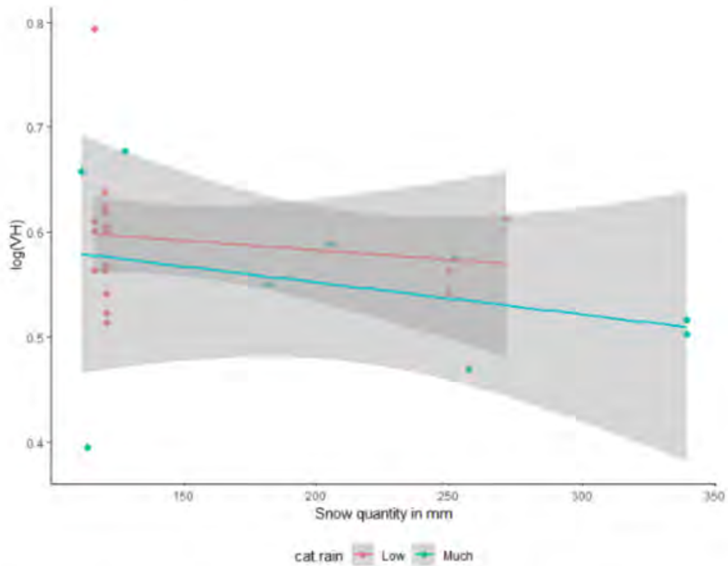

Figure A.8: Relation between snow, rain quantity and vegetative high

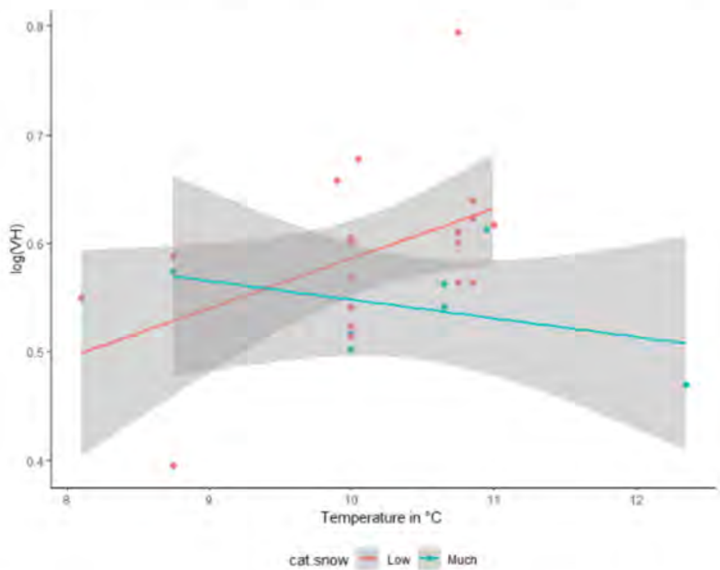

Figure A.9: Relation between temperature, snow quantity and vegetative high

A.2.2 Reproductive height

Here are the outputs of R concerning the reproductive height.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-2.9356	1.2360	-2.38	0.0296
RH$Snow	0.0158	0.0066	2.40	0.0283
RH$Rain	0.0020	0.0015	1.32	0.2029
RH$Temp	0.3115	0.1075	2.90	0.0100
RH$Snow:RH$Rain	-0.0000	0.0000	-1.48	0.1584
RH$Snow:RH$Temp	-0.0014	0.0006	-2.37	0.0298

Residual standard error: 0.1007 on 17 degrees of freedom
Multiple R-squared: 0.3968, Adjusted R-squared: 0.2193
F-statistic: 2.236 on 5 and 17 DF, p-value: 0.09787

Table A.2: Influences of variable on reproductive height

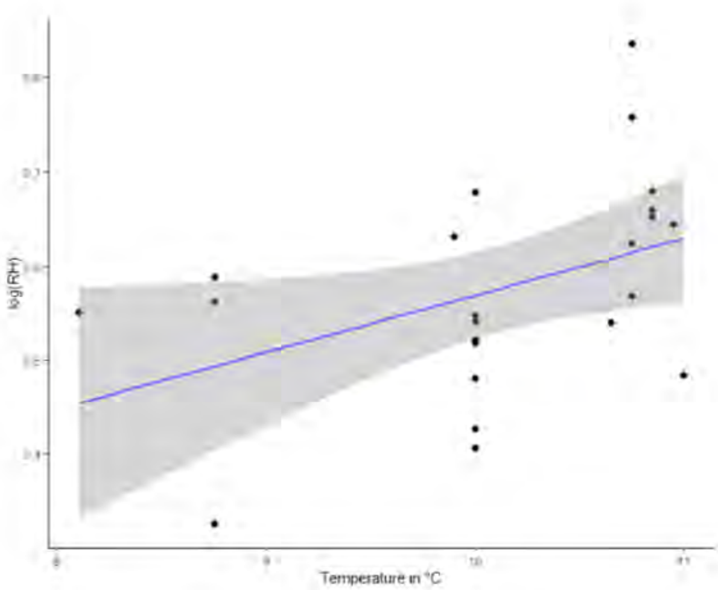

Figure A.10: Relation between temperature and reproductive high

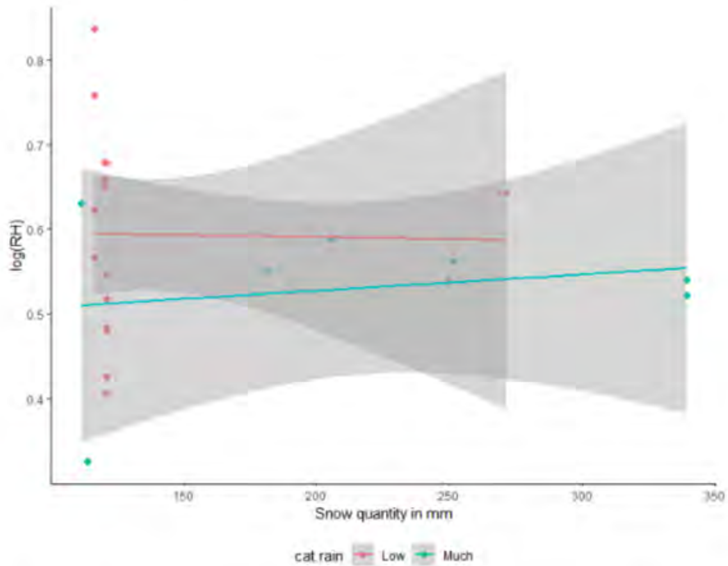

Figure A.11: Relation between snow and reproductive high

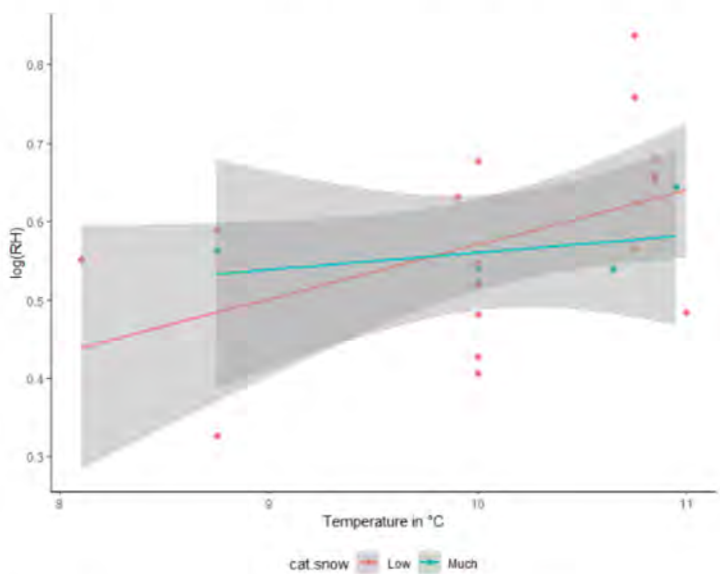

Figure A.12: Relation between temperature, snow quantity and reproductive high

A.2.3 Leaf width

Here are the outputs of R concerning the leaf width.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	8.0515	3.8711	2.08	0.0564
LW$Snow	-0.0370	0.0231	-1.60	0.1320
LW$Rain	-0.0513	0.0227	-2.26	0.0401
LW$Temp	-0.7696	0.3750	-2.05	0.0593
LW$Snow:LW$Rain	0.0002	0.0001	1.81	0.0922
LW$Snow:LW$Temp	0.0036	0.0022	1.62	0.1270
LW$Rain:LW$Temp	0.0052	0.0022	2.32	0.0360
LW$Snow:LW$Rain:LW$Temp	-0.0000	0.0000	-1.84	0.0863

Residual standard error: 0.04725 on 14 degrees of freedom
Multiple R-squared: 0.5138, Adjusted R-squared: 0.2706
F-statistic: 2.113 on 7 and 14 DF, p-value: 0.1106

Table A.3: Influences of variable on leaf width

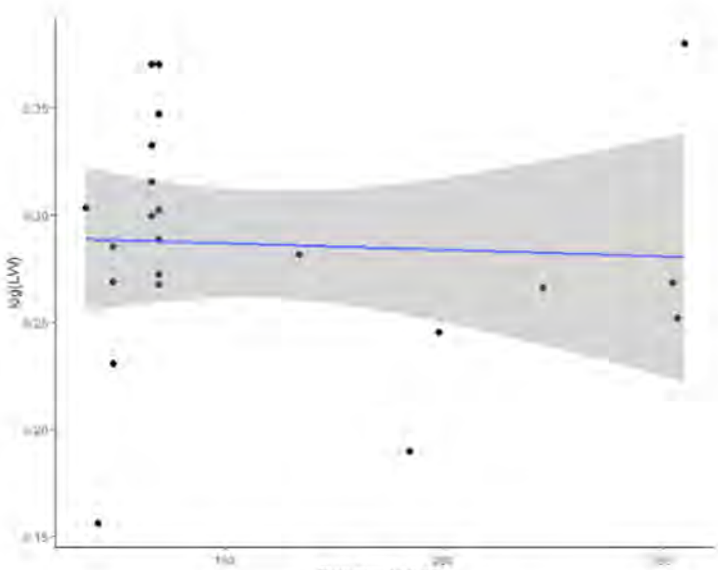

Figure A.13: Relation between rain and leaves width

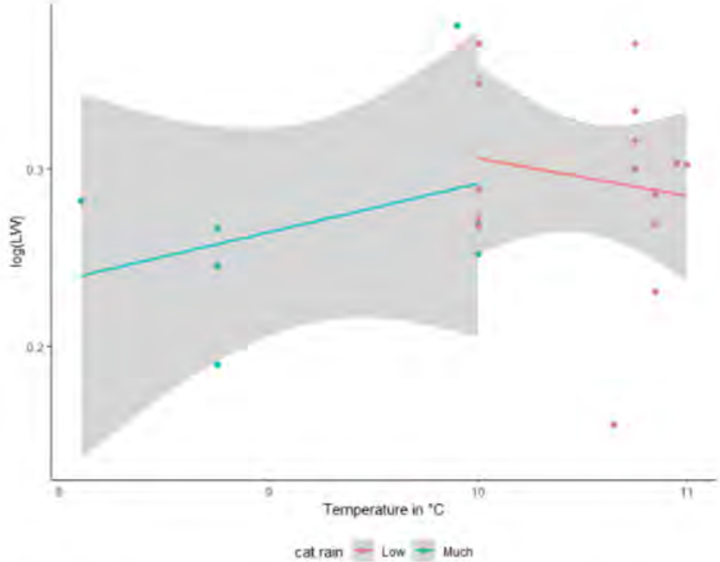

Figure A.14: Relation between temperature, rain quantity and leaves width

A.2.4 Leaf length

Here are the outputs of `R` concerning the leaf length.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.0439	0.1268	-0.35	0.7325
LL$Temp	0.0273	0.0126	2.17	0.0420

Residual standard error: 0.04691 on 20 degrees of freedom
Multiple R-squared: 0.191, Adjusted R-squared: 0.1506
F-statistic: 4.722 on 1 and 20 DF, p-value: 0.04197

Table A.4: Influences of variable on leaf length

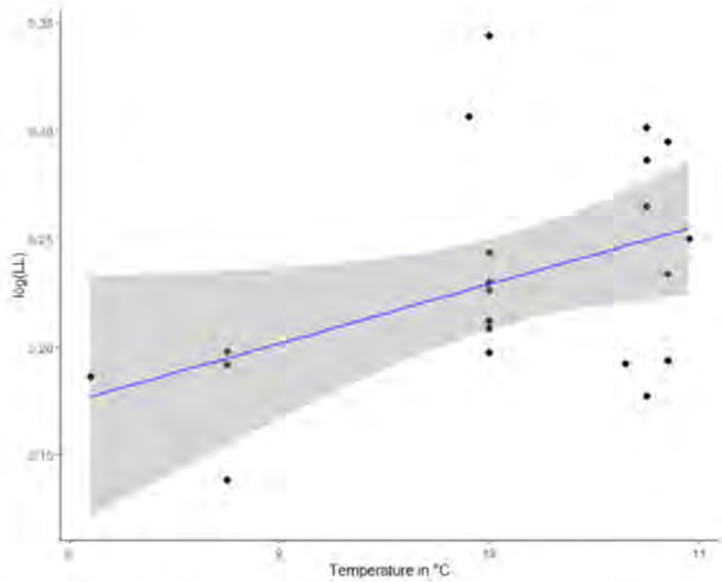

Figure A.15: Relation between temperature and leaves length

A.2.5 Number of leaves

Here are the outputs of R concerning the number of leaves.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-1.9316	1.2086	-1.60	0.1265
nL$Snow	0.0129	0.0059	2.20	0.0406
nL$Rain	0.0025	0.0015	1.63	0.1199
nL$Temp	0.2180	0.1026	2.13	0.0469
nL$Snow:nL$Rain	-0.0000	0.0000	-1.89	0.0739
nL$Snow:nL$Temp	-0.0011	0.0005	-2.11	0.0484

Residual standard error: 0.1059 on 19 degrees of freedom
Multiple R-squared: 0.2318, Adjusted R-squared: 0.02967
F-statistic: 1.147 on 5 and 19 DF, p-value: 0.3705

Table A.5: Influences of variable on number of leaves

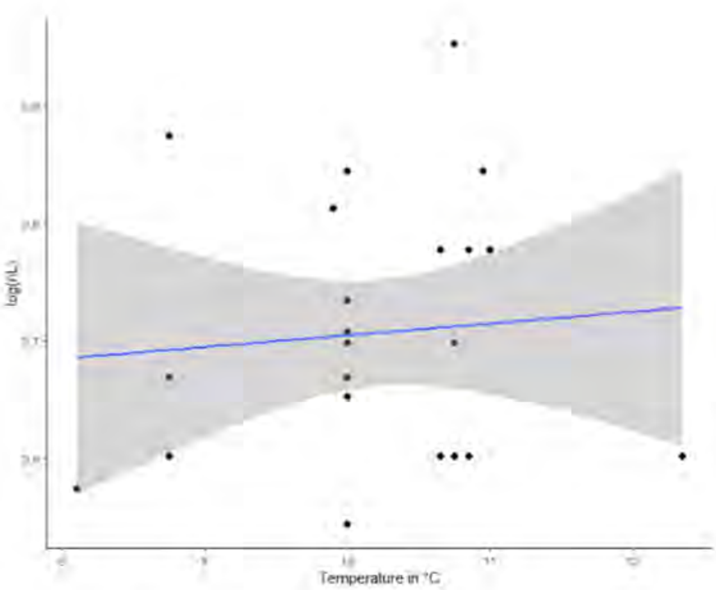

Figure A.16: Relation between temperature and number of leaves

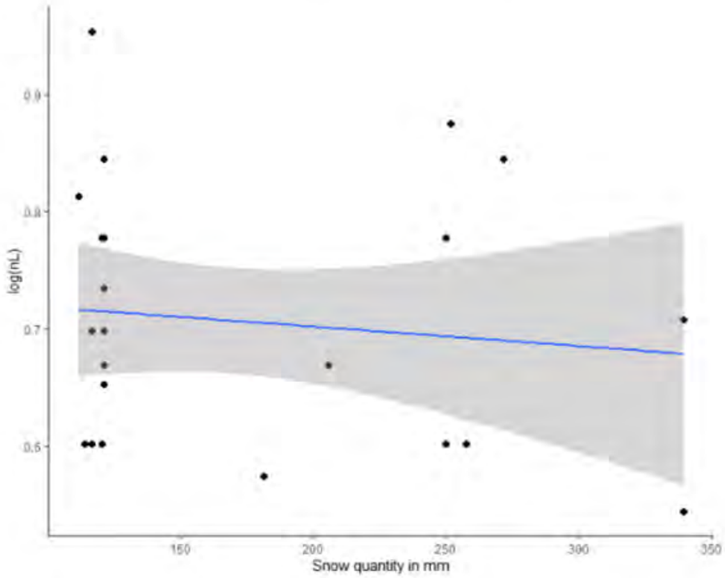

Figure A.17: Relation between snow and number of leaves

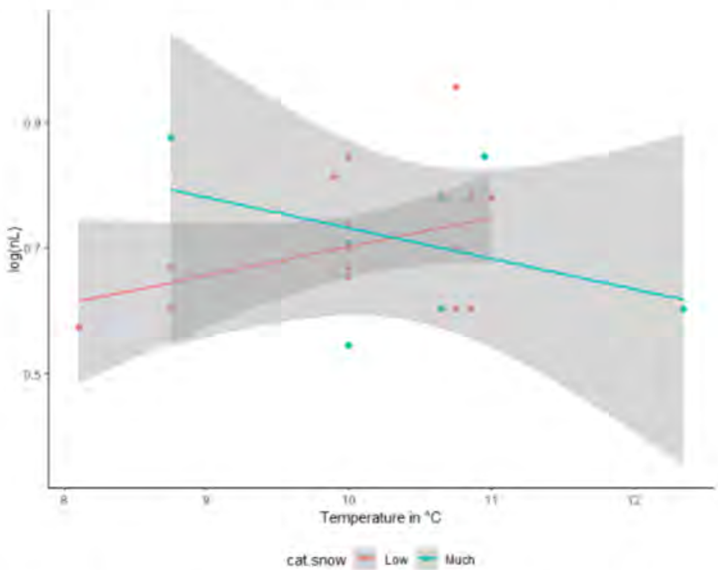

Figure A.18: Relation between snow, rain quantity and number of leaves

A.2.6 Number of inflorescences

Here are the outputs of R concerning the number of inflorescences.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.1196	0.2700	-0.44	0.6630
nI$Snow	0.0011	0.0007	1.64	0.1181
nI$Rain	0.0011	0.0008	1.34	0.1971
nI$Temp	0.0246	0.0185	1.33	0.2003
nI$Snow:nI$Rain	-0.0000	0.0000	-1.58	0.1320

Residual standard error: 0.05761 on 18 degrees of freedom
Multiple R-squared: 0.1814, Adjusted R-squared: -0.0004821
F-statistic: 0.9973 on 4 and 18 DF, p-value: 0.4345

Table A.6: Influences of variable on number of leaves