

DEPARTMENT OF BIOLOGICAL AND ENVIRONMENTAL SCIENCES

ARCTIC PLANT COMMUNITIES RISE WITH TEMPERATURE

Plant functional traits as a tool to predict global climate change



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Abstract

Global warming occurs at a rate at least three-fold in the arctic regions compared to the rest of the world. Here, plant community functional traits were assessed in response to experimental warming in three arctic areas of Fennoscandia (Latnajajure, Abisko and Kilpisjärvi). Temperature was manipulated using Open Top Chambers (OTCs) of 1 m², which induced local temperature increases ranging between 1.5-3°C in randomly selected plots within each arctic site. Functional traits at a community level were compared between the temperature manipulated and control plots. The traits assessed were either associated with plant growth: height and leaf area, or with the economic resource spectrum: Leaf Dry Matter Content (LDMC), leaf nitrogen content (leafN) and Specific Leaf Area (SLA). Plant community height was significantly greater in temperature manipulated plots, indicating that exposure to increased temperature cause plant communities to become taller. To better understand the potential consequences of changes in functional traits for arctic ecosystem functioning, a thorough literature review on plant functional trait variations and their possible association with climate change feedback mechanisms was performed. This review revealed several potential feedback mechanisms associated with increased plant height that affect global warming in the arctic regions. However, whether taller plant communities cause global warming to accelerate, decelerate or stay the same in an even warmer future depends on the balance between these positive and negative feedback mechanisms. For example, reduced albedo due to taller plants create more heat absorption by the earth's surface, accelerating global warming. Yet, at the same time, woody plants that grow taller have a larger capacity to store carbon, resulting in reduced atmospheric carbon and, thus, a deceleration of the temperature increase.

Key words: Arctic warming, plant functional traits, Community Weighted Mean, vegetational changes, global climate change

Sammanfattning

I de arktiska områdena sker den globala uppvärmningen i en hastighet som är minst trefaldig jämfört med resten av världen. I denna studie undersöktes funktionella egenskaper hos växtsamhällen som blivit utsatta för ökad temperatur, med syftet att förstå hur framtidens förutspådda temperaturökning påverkar arktiska växtsamhällen. Vidare undersöktes också hur ändringar i arktisk vegetation i sin tur kan påverka det globala klimatet genom så kallade feedback mekanismer. Slumpmässigt utvalda växtsamhällen i tre arktiska områden i Fennoskandia (Latnjajaure, Abisko och Kilpisjärvi) temperaturmanipulerades med hjälp av open top chambers (OTCs). OTCs är 1 m² stora kammare som inducerar en lokal temperaturökning om 1.5-3°C. Funktionella egenskaper som antingen var associerade med växttillväxt: höjd och bladarea, eller associerade med det ekonomiska resursspektrumet: förhållandet mellan torr och blötvikt (LDMC), bladens kväveinnehåll (leafN) och specifik bladarea (SLA) undersöktes och jämfördes mellan de temperaturmanipulerade och icketemperaturmanipulerade områdena i de tre arktiska regionerna. Växtsamhällenas höjd var signifikant högre i de temperatur-, jämfört med de icke-temperaturmanipulerade områdena, vilket indikerar att växtsamhällen blir längre vid ökad temperatur. För att bättre förstå potentiella konsekvenser av växtförändringar inom arktiska ekosystem gjordes också en litteraturstudie om arktisk växtvariation och dess möjliga samband med klimatförändringars feedback mekanismer. Denna litteraturstudie avslöjade flertalet potentiella feedback mekanismer associerade med ökad höjd av växtsamhällen som påverkar global uppvärmning i arktiska regioner. Huruvida längre växtsamhällen resulterar i att hastigheten för global uppvärmning ökar, minskar eller bibehålls beror dock på balansen mellan dessa positiva och negativa feedback mekanismer. Exempelvis orsakar minskad albedo (som kan vara ett resultat av längre växtsamhällen), ökad värmeabsorption av jordens yta, vilket accelererar den globala uppvärmningen. Samtidigt orsakar mer biomassa av trädstammar (som är ett resultat av längdtillväxt) att växtsamhällen sammantaget har en större kapacitet att lagra kol, vilket resulterar i mindre atmosfäriskt kol och, således, en minskad hastighet för global uppvärmning.

Introduction

The Arctic tundra is rapidly changing due to climate change. Vegetational changes in these ecosystems may have key implications for different feedback mechanisms on global climate. By manipulating the temperature that plant communities experience *in situ*, the effect of temperature on plant functional traits can be observed, which allows for a possible prediction of future variations among arctic plant communities in a warming climate. Understanding the shifts in plant-trait variation can further lead to an improved understanding of potential future global climate feedbacks, which have implications for whether the global warming will be accelerated, decelerated, or stay the same.

Plant functional traits

Plant functional traits are essential in understanding vegetational changes and their effect on key ecosystem functioning (Yang, et al., 2015). The latest IPCC report states that global surface temperature was 1.10°C higher in 2021 than 1850-1900, the first period of sufficient global temperature monitoring, and that arctic temperatures is increasing three times as fast as the global average (IPCC, 2021). Arctic plant communities induce different feedback mechanisms to global warming. Understanding the effect of global warming on plant communities in the arctic is, therefore, key to understand future global climate feedbacks that in turn are induced by arctic plants. Increased temperatures are linked to decreasing bare grounds, while shrub and graminoids increases in abundance (Myers-Smith, et al., 2011). Shrub expansion both across latitude and elevation along mountain slopes is probably the most notable vegetational change in the arctic (Myers-Smith, et al., 2011).

Traditional understanding of functional change in the tundra biome has been conducted through studies on a functional group level, e.g., forbs and shrubs. However, looking at functional groups alone does not give an explanation to variations of the commonly measured traits (Thomas, et al., 2018). Within functional groups there is a lot of interspecific trait variation, hence an approach of looking at interspecific trait variation can increase the understanding of plant community traits in response to temperature changes (Siefert, et al., 2017). Plant functional traits can be defined as morphological, phenological or physical characteristics of plants, influenced by the environment, that affects the fitness of any individual (Violle, et al., 2007). Variation in plant functional traits can be linked to environmental, e.g., climatic, variation. This is due to plant functional traits reflecting the interaction between the plant and its habitat (Moles, et al., 2009, Bjorkman et al., 2018b). Changes in community functional traits influence the ecosystem functioning and thereby environmental changes. The community-level functional trait approach differs from that of measuring traits on individuals, as it better takes into consideration and reflects intraspecific trait variation. Studying single traits will give an understanding of how individuals vary, plasticity and interspecific trait variation, given the current circumstances, but not the general variation across all individuals of the study area. Instead, estimates of traits on community-level representing the communityweighted mean trait value of all species within the study site, is a greater approach to predict plant communities. Hence species turnovers and abundance shifts are accounted for when taking a community-level approach (Zanzottera, et al., 2020).

Plant community height has increased rapidly across the arctic over the past few decades. Yet, changes in leaf traits, although shown to vary largely along biogeographic gradients, is still to discover. Traits relating to community plant size can be associated to above ground effects of tundra ecosystems, such as changes in albedo, hydrology (*e.g.*, soil moisture and snow cover) and carbon stocks bound to plants and are relatively well studied. On the other hand, traits related to below ground effects, such as nutrient turnover, soil carbon storage and degradation of leaf litter are relatively understudied (Myers-Smith, et al., 2019). In this category, referred

to as the resource economics spectrum, specific leaf area (SLA), leaf dry matter content (LDMC) and leaf nitrogen content (leafN) is included (Wright, et al., 2004). LDMC is the quote between leaf dry mass and leaf wet mass, reflecting the leaf's ability to capture light and photosynthesize (Wang et al., 2022). Plants with high LDMC have been shown to have a lower growth rate (Suter & Edwards, 2013). Specific leaf area (SLA) is the ratio of leaf area to leaf dry mass. There is typically a positive correlation between relative growth and SLA and a negative correlation between SLA and the life span of leaves (Reich et al., 1992). This indicates that leaves with high SLA have a greater production rate but shorter life span.

Arctic plant communities induce feedback mechanisms affecting global climate

Arctic plant communities change due to ongoing climate change and such changes have implications on global climate change. When arctic plant communities undergo changes, certain climate feedbacks are induced, altering the amount of free atmospheric carbon and, therefore, also the atmospheric warming. The two main positive feedback mechanisms (*i.e.*, positive meaning mechanisms that accelerate the temperature increase), is reduced albedo due to reduced snow coverage and permafrost thawing due to effects on the free atmospheric carbon.

Reduced albedo

Albedo is the amount of solar energy reflected by the earth's surface back into the atmosphere. When a surface is covered by snow, approximately 90% of the solar radiation is reflected by the earth's surface back to space. However, as snow and ice are lost due to warming or plant expansion, the amount of solar radiation reflected by earth is reduced. Albedo loss results in solar absorption gain, meaning that the amount of solar radiation that the earth absorbs is increasing. Such solar absorption gain, therefore, heats the planet. Albedo effects are mainly seen where sea ice retreats. When it comes to warming, melting sea ice during the summer period alone is equivalent to adding an additional 25% to the atmospheric CO_2 (Pistone et al., 2014). In winter, shrubs affect the albedo negatively (*i.e.*, the albedo is reduced) by having branches that reaches through the snow, and during spring and sprouting a similar effect is observed since the first spring leaves reaches above the snow cover (Sturm et al. 2005).

Permafrost thawing

Large amounts of arctic soils are permanently frozen, so-called permafrost soil. The permanently frozen soils in the arctic store almost 50% of the global soil carbon (Schuur 2015). Both in the form of carbon dioxide but also the more potent greenhouse gas methane (Saunois et al., 2020, Nauta et al., 2015). They are key components for arctic plant communities by influencing moisture, nutrient availability, and carbon exchange. Due to accumulation of biomass during more than 10 000 years these permafrost soils store a large amount of the earth's carbon stocks. Annual freezing variation of the top layer, the active layer, depends on the surrounding air temperature. In winter the active layer freezes and conserves the permafrost layer, while in spring the active layer thaws. With an extended spring season thawing occur both earlier and is prolonged, which degrades the permafrost layer and result in greenhouse gas emissions. As plants interact with the soil, they can alter the permafrost stability and, thereby, alter the carbon cycles (Keuper et al., 2020). Larger plants like shrubs, forbs and graminoids, function as natural snow fences and catches snow around them causing local increases in snow depth. During winter season the snow insulate the soil and increases the soil temperature. A difference between the air and soil temperature can be as large as 30°C (Sturm et al., 2001). Increased soil temperatures prevent the refreezing of permafrost layers, resulting in induced permafrost thawing. Further, soils are thought to increase the microbial activity and, therefore, the nutrient cycles. In turn, decomposition of dead plant matter due to such microbial activity effects the global carbon cycle with higher decomposition rates releasing more atmospheric

carbon. Microbial activity not only affects carbon fluxes but also nutrients such as nitrogen and phosphorus are affected. Thus, increased microbial activity results in positive feedback on shrub growth because of increased nutrient availability. However, in an experimental study assessing artificial shrub canopies in manipulated and unmanipulated plots in arctic Canada, no significant results regarding neither ammonium nor nitrate absorption was found (Myers-Smith & Hik, 2015a). During summer, tall shrubs shade the soils, reducing the influx of sunlight for other plants surrounding the shrubs. Higher canopies increase the availability to solar energy, resulting in higher competition and ultimately, in lower plant diversity (Pajunen, et al., 2011).

Negative feedback mechanisms

Large plants with woody stems induce negative climate feedback as they incorporate carbon as biomass and, thereby, removes carbon from the atmosphere. Thus, as woody plants grow taller, more atmospheric carbon is incorporated as biomass, lowering the atmospheric carbon and the atmospheric warming. This feedback is greater for evergreen than deciduous shrubs. While deciduous shrubs undergo senescence of leaves by the end of each growing season leading to increased organic litter, evergreen shrubs detach their leaves only once every few years, and not all at once. However, evergreen leaves have a longer degradation time and lowers the rate of the carbon cycle (Vowles and Björk, 2019).

Aim & hypothesis

The aim of this study is to understand how plant functional traits at the community-level respond to increased temperature. The community-level approach combines the functional traits of all individual species observed within an ecological community. Temperature is manipulated via Open-top chambers (OTC) placed over experimental plots within the study sites and both above- and below-ground plant community traits are assessed. The project also aims to connect any observed changes of plant functional traits in relation to temperature with previously known plant feedback mechanisms towards climate change.

Objectives:

- How does experimental warming influence plant functional traits at the community level?
- Do shifts in the functional traits, which are responsive to warming, have any implications for climate feedback mechanisms?

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Hypotheses

I hypothesize as follows:

- Since previous studies on experimental warming have shown increased height looking at intraspecific trait variation I expect: With OTC warming exposure present, both plant maximum height and leaf size will increase, indicating that plant functional traits associated with plant growth, will increase in warmer climates.
- Traits associated with the resource economics spectrum will correlate with plant size giving a negative correlation for LDMC, *i.e.*, with greater height and leaf size, LDMC will be lower. This is because high LDMC has been shown to be negatively correlated with growth rate. Both SLA and leaf nitrogen content have been shown to relate to

growth function and, therefore, both of these traits are expected to have a positive correlation with increasing community growth.

• Changes in vegetational patterns have previously been shown to alter climate feedback mechanisms in several different ways. I therefore expect plant functional traits responsive to warming will have implications on plant feedback mechanisms affecting climate change, such as altering albedo and carbon storage.

Material and methods

Acquisition of field data

The project is based on data collected through the International Tundra Experiment (ITEX). ITEX sites use clear-sided hexagonal open-top chambers (OTCs) to locally increase the temperature (Molau, et al., 1996). These chambers will typically increase the temperature by \sim 1,5-3°C, but can also affect other parameters than temperature, such as soil moisture, wind exposure and snow coverage. For this project data will be used from 3 out of 60 temperature manipulated sites in the ITEX network. All sites are situated in either Sweden or Finland (*see site descriptions below*) in treeless tundra ranging between 68-70° in latitude. Within each of the three sites a subset of 5-24 randomly selected plots were treated with OTCs and subsequently compared with the same amount of unmanipulated plots in the three arctic sites.

Site descriptions

Abisko (68.328400, 18.835600)

The Abisko valley lies south of lake Torneträsk in the county of Norbotten, Sweden. Abisko is located 200 km north of the arctic circle, and although being situated furthest north in Sweden, the site is considered as low-arctic. The Mean Annual Air Temperature (MAAT) is -1.7° C (Climate-data.org). Data for this study was collected at a site ~ 3 km southeast from Abisko research station along the northwestern slope of Mt. Nissoncorru. During the year 2012 data was collected from 12 OTC manipulated plots and 6 control plots around 400 meters above sea level (m.a.s.l) in an area considered as wet. The year after, 2013, data was collected from 5 OTC plots and the equal amount of unmanipulated plots further down the mountain slope, around 340 m.a.s.l, in an area dominated by peatland structure.

Latnjajaure (68.355720, 18.495310)

14 km west of Abisko lies the Latnjajaure field station, located 1000 m.a.s.l., by the lake with the same name. The lake is surrounded by a U-shaped glacial valley and lays around 750 meters above the tree line. Data for this project was collected at the western slope of Mt. Latnjacorru. Vegetation is typical for the southern arctic regions but with higher species diversity due to soil properties and soil moisture (Scharn, et. al., 2021b). Extensive climate data collection detects a MAAT of - 1.7°C and a temperature increase of 0.3°C per decade (Scharn, et. al., 2021b). Three years of data collected in the Latnjajaure was used for this project. In 2013, plots were put out in three different ground environments. A poor heath area considered as dry, carried 4 OTC plots respectively 4 control plots. 4 treated plots and 4 control plots were sampled in a rich meadow area that is considered moist. The last area sampled in 2013 was one considered as wet (wet meadow), were 5 OTC treated and 5 control plots were sampled. During 2014 two dry areas were sampled. the first one was a dry meadow with 4 OTC plots and 4 control plots and the second one was a dry meadow with 5 OTC treated plots and 5 unmanipulated plots. 3 plots treated with OTC and 3 control plots were sampled in a wet area, a tussock tundra. The largest sample size was collected during 2016 at which time five subsites were sampled. These were two subsites in dry areas, dry heath and dry meadow. In the dry heat subsite 4 plots of each treatment were sampled and in the dry meadow 5 plots for each treatment was sampled. One subsite was considered moist, mesic meadow, where 6 plots of each treatment was sampled. The last two subsites were considered wet, tussock tundra and wet meadow. For both wet subsites, tussock tundra and wet meadow, 5 plots of each treatment was sampled.

Kilpisjärvi (69.068000, 20.819900)

Kilpisjärvi is located north of lake Kilpisjärvi, that shares a border between Finland and Sweden. MAAT in Kilpisjärvi is - 2.2°C (climate-data.org) and is located around 600 m.a.s.l. Data collection in this project was performed in the valley between Mt. Johakkus and Mt. Saana, above the tree line on the tundra. Vegetation in the area around Kilpisjärvi has been documented to be influenced by herbivory (Eskelinen & Oksanen, 2006). The same subsites were sampled in Kilpisjärvi for all three years, 2013, 2016 and 2019, in an area considered as moist.

Data collection in field

The plant data have been collected using a point-intercept method according to the protocol of community baseline measurement for ITEX studies (Molau, et al., 1996). According to this protocol, a selected area is marked with a square pattern using lines horizontally and vertically *i.e.*, X- and Y-lines. The point where the lines meet function as coordinates for the plot measured, each plot is $\sim 1 \text{ m}^2$. Within each site several plots were randomly selected to be provided with an OTC chamber. To calculate plant abundance of each species within each plot, every species was counted the number of times found in every plot. Relative abundance was then calculated by taking the number of each species divided by number of total individuals counted. Plant composition data used in this project was collected between 2012 and 2019.

The trait data in this study was provided by the TRY database (try-db.org). A total of five plant functional traits was assessed: two traits regarding plant size, *i.e.*, height and leaf size and three traits reflecting the resource economics spectrum: specific leaf area (SLA), leaf dry matter content (LDMC) and leaf nitrogen content (leafN). All traits analyzed were measured using the *New handbook for standardised measurement of plant functional traits worldwide* (Pérez-Harguindeguy, et al., 2016).

SLA values is a quota between the leaf area (mm²) and the dry mass of the leaf (mg), while LDMC is derived from the quota between the leaf dry mass and the leaf wet (fresh) mass. Following equations are used to calculate the two different functional traits:

$$SLA = \left(\frac{Leaf area (mm^2)}{Leaf dry mass (mg)}\right) \qquad \qquad LDMC = \left(\frac{Leaf dry mass (mg)}{Leaf wet mass (mg)}\right)$$

Data analysis and statistics:

From the raw data, only vascular plants were extracted. Bryophytes and lichens were removed for this study since no trait data were available for these groups. Observations of litter and soil was also removed from the data set. All sorting and cleaning of the raw data was performed using the Dplyr:: R package. The raw data for species composition observed in the field was collected since 1994, but only the years of 2012-2019 was analyzed in this project. To extract trait data from the TRY database, the species present within the different sites were extracted. These were then used to extract functional trait data relevant for the project. Each species received a trait value for each of the five different functional traits. The TRY database carries a large number of measurements for each trait and species and a mean value of each measurement, therefore, resulted in a specific trait value for each species. Species missing trait values were accounted for by extracting a mean from species within the same genus that carried specific trait values. This was true for Lingon berry, *Vaccinium vitis-idaea*, and Water sedge,

Carex aquatilis var. minor. The sub species Mountain crowberry, *Empetrum nigrum ssp. hermaphroditum*, was counted as common Crowberry, *Empetrum nigrum*. The specific trait values for each species were used calculate a community weighted mean (CWM) for each plot. CWMs was used since species differ in abundance and contribute differently to the community mean. The CWM value is calculated by taking each specific trait value weighted by the abundance of each species (Bjorkman. et al., 2018a). Calculations for CWM values of each plot was performed in R using the community.weighted() function within the Dplyr:: R package, according to following equation:

$$CWM = \left(\frac{\sum_{i}^{n} = 1 \ w_{i} X_{i}}{\sum_{i}^{n} = 1 \ w_{i}}\right)$$

$$n = number of \ traits \ to \ be \ averaged$$

$$w_{i} = weights \ applied \ to \ trait \ values$$

$$X_{i} = trait \ values$$

All CWM data, for both treatment groups, were tested to meet assumptions of normality using a Shapiro Wilk's test. If proven not to be normally distributed the data was transformed using log, sqrt, and log10. If data was normally distributed, either before or after transformation, a Welch's independent two sample t -test was performed for the formula 'trait ~ treatment'. This was performed using a confidence interval of 95%. Testing for differences between treatment and control group was conducted individually for each site and year. If data was normally distributed the Welch two sample t-test for individual groups was conducted, using t.test() function within stats:: R package. Null hypothesis was set to means = 0, and that data was two sided. When data was not normally distributed a Wilcoxon, Mann-Whittney U test was performed, using the wilcox.test() function within stats:: R package. A linear model was constructed to search for variances between treatments across the different years at each site. This was done by using the lm() function from stats:: R package. The model constructed was:

CWM Trait ~ Treatment + Year

Testing for variance was done through an ANOVA, using the anova() function from stats:: R package. All statistical work was performed in R, version 4.0.3 GUI 1.73 Catalina build.

Qualitative study of literature regarding plant feedback mechanisms on climate change

A qualitative approach of existing knowledge of plant feedback mechanisms concerning climate change was used to connect observed variation of plant functional traits in response to warming. This was done by using different combinations of key words in the function "Supersök" at the library of Gothenburg University. Primarily, publications with results connected to height expansion of arctic communities was searched for. All publications found that indicated a shift to taller plants in arctic plant communities was gathered in a table to get an overview of the extent over the current research, however, publications indicating that plants increase in height due relation to herbivory action was not included. Thereafter, the key words were changed in order to find publications about climate feedback mechanisms associated with taller plants.

Key words first search:

Shrub height, vegetation change, arctic tundra, shrubification, subarctic region, shrub expansion, tundra ecotone, deciduous shrubs, evergreen shrubs *Key words second search:*

All of the above AND climate change, climate feedback, albedo.

Results

Functional trait data

The CWM was significantly greater for the experimentally warmed compared to the control plots in Latnjajaure in both 2013 and 2016 (Figure 1; Table 1; 2013 P=0.0297 and 0.0409 for 2013 and 2016, respectively). No significant results regarding plant community height were found in 2014 at Latnjajaure (Appendix 2.1). Height was not significantly affected by experimental warming at the other two sites, and no other functional traits were significantly influenced by experimental warming at any site (Appendix 2.1).



Figure 1. Displayed are traits from open-top chambers (OTC) temperature manipulated plots (OTC treated; orange bars) and unmanipulated control plots (Control; grey bars) from plant communities in Latnjajaure for the years **A)** 2013 and **B)** 2016. Data presented as boxplots show the functional trait values for each trait assessed, *i.e.*, height, specific leaf area (SLA), leaf nitrogen content (leafN), leaf dry matter content (LDMC) and leaf area. Outliers are displayed by black circles.

To determine whether species abundance influenced OTC treated plots to have a greater height influencing community height in the communities of Latnjajaure, weighted values of height (the CWM value of each plot) was compared with the normal mean value of each plot (Figure 2). For the year 2013 height was significantly greater in the CWM group. This indicates that taller species are more abundant than shorter species in the OTC treated plots. For the other two years, 2014 (B) and 2016 (C), a trend towards the same result was suggested.

Table 1. Results from Welch's independent two sample t-test and Mann-Whitney U test (*) shows a significant p value, CI = 95%. After t-test performed a t-value is presented in the left column, for the Mann-Whitney U test this is presented as W = $1 - n_1(n_1+1)/2$ (n_1 = number of observations in first group).

| Latnjajaure | t (t-test)∕ W(ManWU) | df | p-value |
|---------------------|----------------------|----|---------|
| 2013 | | | |
| Height ~Treatment | 41 | | 0.0297* |
| Leafarea ~Treatment | -0.4449 | 22 | 0.6609 |
| SLA ~Treatment | -0.2506 | 23 | 0.8044 |
| LDMC ~Treatment | 85.5 | | 0.9795 |
| LeafN ~Treatment | -1.5969 | 21 | 0.1255 |
| 2016 | | | |
| Height ~Treatment | -2.1096 | 46 | 0.0409* |
| Leafarea ~Tratment | 298 | | 0.7878 |
| SLA ~Treatment | -0.5817 | 44 | 0.5637 |
| LDMC ~Treatment | 262 | | 0.3351 |
| LeafN ~Treatment | 336 | | 0.6581 |

Common for all years in latnjajaure were outliers detected for each CWM data set. Within these outlier plots the species mostly contributing to the higher CWM value is the tea-leaf willow, *Salix phylicipholia*, and for the outlier year 2016 also the Common juniper, *Juniperus communis*. Results from all sites regarding the difference between CWM and normal mean are presented in appendix 2.3.



Figure 2. Differences in the functional trait height between community weighted mean (CWM) values (Height CWM; black bars) and normal mean values (Height mean; green bars). **A-C)** represents the results from the years 2013, 2014 and 2016, respectively.

Height in Latnjajaure was significantly different during the different years both regarding the effect of year and treatment. The year effect in Latnjajaure was significantly different for the different years (Figure 3; P=0.04). This indicates that mean height varies across communities independent of treatment, *i.e.*, community height is greater for both OTC treated- and control plots during different years. The treatment effect was consistent during all the years (Figure 3; P=0.043), indicating that the effect of temperature manipulation via OTCs is consistent regardless of what year it is. Results from all sites and traits during the different years are presented in Appendix 2.2.



Figure 3. The figure displays the differences in functional trait height for open-top chambers (OTC) temperature manipulated plots (OTC treated; orange bars) and unmanipulated control plots (Control; grey bars) for the different years in Latnjajaure (2013, 2014, & 2016).

Discussion

The effect of experimental warming on plant functional traits

Plant height increases, *e.g.*, the plant communities grow taller when exposed to experimental warming with OTCs in the arctic. Thus, this indicates that arctic plants are prone to grow taller if the average temperature increases, a scenario certain to occur in the future. Leaf area on the other hand, which is the other functional trait associated with plant growth, did not show any correlation with temperature but was maintained across OTC-treated and unmanipulated control plots. None of the functional traits representing the economic resource spectrum, changed in response to higher temperatures.

Arctic regions are especially exposed to and affected by global warming. In fact, the rate of global warming in the arctic occur at a rate much faster than the global average. These environmental changes result in numerous directional changes for arctic plant communities. Studying plant functional trait variations can be used as a tool to understand future plant community changes. Identifying trait variations induced by climate change may also help us understand the potential consequences of Arctic vegetation change for feedback mechanisms on global warming.

Plant height

Of all functional traits studied in this project, plant height was the only one to show positive correlation with temperatures. Still, this positive correlation was only found in one of the three test sites, Latnjajaure. Increasing plant height, at community level, is generally considered among scientist as the major effect of temperature acceleration (Bjorkman, et al., 2018a; Hudson et al., 2011; Myers-Smith et al., 2019). Even though plant height was increased at OTC treated plots in Latnjajaure and not in any other site, it is also important to consider that other abiotic factors than temperature were excluded from the analysis and thus, the effect of such factors are here unknown. Previous studies indicate correlations not only between height and temperature, but also between height and temperature combined with soil moisture (Elmendorf et al., 2011, Bjorkman et al., 2018a, Scharn et al., 2021a). For example, evergreen shrubs were not associated with temperature, but with soil moisture (Elmendorf et al., 2011). Thus, combining both temperature differences and soil moisture measurement explains why height increased only at one site and not others. Temperature changes can be studied either via experimental warming with OTC chambers, latitudinal gradients or through a time series.

Leaf traits - Leaf area, SLA, LDMC & LeafN

The variance explained by different years were significant for the sites Abisko and Latnjajaure, suggesting that seasonal differences affect the leaf area. The functional trait leaf area is sensitive for the period of data collection because arctic plants have a short growth season and measurements may have been performed when growth is not at max. Thus, specific trait values of leaf area can be unreliable. Species living in the arctic must endure harsh environments and have different reproductive cycles than plants from more suitable environments. For example, species such as within the willow genus, *Salix sp.*, does not evolve more leaf than 2 in the first five years of its lifetime (Wager, 1938).

No significant results were found regarding SLA and temperature, which agrees with previous studies (Bjorkman et al., 2018a). The study performed by Bjorkman et al. (2018a) suggest looking into other abiotic variables that may influence SLA, such as soil moisture. SLA has been shown positively correlated to growth, while the life span of plants with high SLA values is negatively correlated (Reich et al., 1992). Hence SLA can be a tool for predicting species composition life spans and strategies. Studying SLA in arctic areas of Canada under experimental warming suggest a decrease in SLA due to energy investments of leaf structure (Hudson et al., 2011). Understanding LeafN is complex since it is dependent on multiple variable factors. Such factors are nitrogen sources in the soil, plant association with Mycorrhiza and different types of nitrogen both available and possible to take up (Evans, 2001). In this study no significant relation was found between LeafN and temperature. This aligns with a study performed next to the Alexandra Fiord in Ellesmere Island, arctic Canada, where eight functional traits were measured for plants exposed to experimental warming. While leaf carbon content increased in OTC treated groups leaf nitrogen content did not (Hudson et al., 2011). During the same study in Ellesmere Island, no difference for LDMC was displayed in the temperature manipulated sites. In fact, there was very little variance between OTC treated plots and control plots for all different species tested (Hudson et al., 2011). Savanna grasslands was studied for LDMC within different functional species groups. There it was found that temperature was a limitation for LDMC variation. The largest effect on LDMC values was because of moisture (Wayne Polley et al., 2020).

Since neither leaf area nor any of the traits regarding the resource economics spectrum could be explained by warming, other environmental factors should be included to understand variation of said traits. Abiotic factors other than temperature is well accounted for to affect resource economic leaf traits within the literature. During a study performed in 117 study sites across the arctic, the effect of both temperature and soil moisture on leaf traits was assessed. All the leaf traits: LDCM, SLA, LeafN and leaf area, were strongly related to soil moisture. In fact, the temperature ~ trait relationship even shifted depending on the soil moisture levels at each site (Bjorkman et al., 2018a). In wet sites temperature had a negative correlation on leafN, while in dry sites leafN increased with higher temperatures (Bjorkman et al., 2018a). During the same study SLA increased with higher temperatures, while LDMC decreased although both traits were much more affected in wet than dry sites (Bjorkman et al., 2018a). Other resources than soil water content may also affect leaf economic traits, such as nutrient availability. A CWM approach was used to the test the influence of soil nitrogen content compared to resource economic leaf traits in France. Here, it was detected that limited nitrogen soil content resulted in higher SLA values while, for LDMC, limited nitrogen soil content resulted in lower values (Perez-Ramos et al., 2012).

Community weighted mean approach

Differences in the community weighted trait mean between control plots and experimentally warmed plots can be due either to differences in species abundance or in differences in species composition among the treatments. The difference between OTC and control plots can be explained by species migration to new areas, in the form of latitudinal shift and upslope movement along mountains (Rew et al., 2020, Mod & Luoto, 2016, Post et al., 2009)). Another potential explanation is that already existing tall species might increase in abundance and thereby affect the community height positively. Difference between CWM values and mean values tells us that taller species are more abundant in temperature manipulated plots. One factor that CWM approach misses is the phenotypic plasticity, *e.g.*, if already existing plant species within the community grow taller regardless of their formal maximum height. Certain species of shrubs have been associated with height increase in arctic plant communities, although not while testing through a community weighted approach. One genus connected with increased height during temperature increase is the Willow, Salix sp. (Forbes et al., 2010, Myers-Smith et al., 2011, Myers-Smith et al., 2011b). In Abisko, both Salix sp. and Juniperus communis migration and expansion have been associated with temperature increase (Halliner & Wilmking, 2011). In this study, plots with extreme community height (looking at CWM values) had one willow species within them, the tea-leaf willow (Salix phyliocipholia). Within one of the plots, the common juniper (Juniperus communis), was present. Both the tea-leaf willow and the common juniper are relatively large shrubs that contributes to a high CWM height value within a community.

Climate feedback

Literature review

During the last years, many articles have been published regarding increasing plant height as an effect of increasing temperatures. One factor said to contribute to taller plant communities as an effect of temperature is shrubification, which implies that shrubs outcompete other phylogenetic groups, mainly forbs and graminoids so that the shrub coverage increase. Current publications regarding height increase in arctic plant communities is summarized in table 2. These studies differ from the present in that they have not studied arctic plant ecosystems by weighing them on abundance, using the CWM. Further, changes in growth patterns in response to temperature have been received using intraspecific trait variation studies for both experimental temperature manipulations (using OTCs), and by studying the ongoing annual real time temperature change. Other studies also involve orthophoto-graphical methods comparing areas from satellite photos between different years.

Increasing plant community height induce feedback mechanisms on atmospheric warming

Potential feedback mechanisms connected with increasing plant community height was collected from several publications during the last decades. The common findings between increasing height of plant communities and their feedback on global climate is schematically depicted in Figure 4. Each positive feedback contributes to an acceleration of an already existing phenomena, hence positive feedback on atmospheric warming accelerates temperature increase. Negative feedback decelerates an already present function, hence negative feedback decelerates temperature increase.

During summer growing season tall plants, mainly shrubs, functions as umbrellas shading the soil locally underneath the plant. Shading of soil will slow down summer permafrost thawing. In turn, this deepens the active layer and slows down the release of greenhouse gases from permafrost layer. Thus, soil shading is an example of a negative feedback on global climate induced by plants growing taller (Blok et al., 2010 & Pearson et al., 2013).

| Table 2. Summary | of current | pulications | related to | height inc | rease in a | rctic communites. |
|------------------|------------|-------------|------------|------------|------------|-------------------|
| | | | | | | |

| Region | Site | Observed vegetational change | References |
|---------------------|------------------------------|---|-------------------------------|
| Alaska | Kenai peninsula | Alder (<i>Alnus</i> within the birch family) shrubs north redirection of shrubline ecotone | Dial, et. al., 2007 |
| Western Canada | Kluane region | North redirection of shrubline ecotone, <i>Salix spp.</i> | Myers-Smith, 2011 |
| | Herschel Island | Increased canopy height & cover of <i>Salix</i> pulchra. Salix spp. Increasing in patch size. | Myers-Smith et al., 2011b |
| Canada | Ellesmere Island | Increasing abundance evergreen shrub and Salix arctica | Hudson, & Henry, 2009 |
| Europe | Abisko, Sweden | Increase in shrub size and upslope movement of <i>Juniperus nana</i> and growth of <i>Salix glauca</i> , <i>Betula nana</i> | Hallinger & Wilmking, 2011 |
| | Cievrratjåkka, Sweden | Empetrum nigrum spp. hermaphroditum increasing abundance | Wilson & Nilsson, 2009 |
| | Nothern Norway & Finland | Predicts increasing shrub cover and mean vegetation height | Muod & Luoto, 2016 |
| | Latnjajaure, Sweden | Increasing shrub cover by the expense of forbs and Graminoides | Scharn et al., 2021B |
| Russia (Siberia) | Yamal-Nenets Okug, Russia | Increasing annual growth <i>Salix lanata & Alnus frtuicosa</i> | Forbes et al., 2010 |

Larger plants act as snow fences and captures snow during the winter, hence deepening the snow cover locally. Deep snow cover isolates the soil and induces higher temperatures in the soil compared locally. Deep snow cover isolates the soil and induces higher temperatures in the soil compared to the surrounding air temperature. Higher soil temperature increases soil microbial activity and thereby soil nutrient availability. This results in better conditions for plant growth and shrub expansion (Chapin et al., 2005, Sturm et al., 2005b, DeMarco et al., 2014). During winter, permafrost thawing is brought to a pause and so with increasing winter soil temperatures this pause is altered. This is an example of a positive feedback mechanisms induced by taller plants resulting in increasing permafrost thawing during wintertime, which accelerates warming (Sturm et al., 2005b, McKiney and Goden, 2010, Haagmans, 2021, Nauta et al., 2015).

Another example of positive feedback on global climate as a result of arctic plants growing taller is that the plants emerge more through the snow cover as they grow and, thus, negatively alters the albedo. Direct effect of lower albedo is increased solar radiation absorption by earth, causing accelerated warming (Beringer et al., 2005, Bonfils et al., 2012). An indirect effect of lower albedo is accelerated spring thaw. The solar energy absorbed by the soil induces permafrost thawing earlier in the spring season, thus increasing the total amount of permafrost thawing annually (Sturm et al., 2005a). Yet another negative feedback mechanism is since larger and taller plants have the possibility to store more carbon in their woody structures, *i.e.*, in their stem and roots. More carbon stored in biomass decelerates the carbon cycle and the amount of free carbon particles in the atmosphere, decelerating global warming (Myers-Smith et al., 2015b, Garcia Criado, et al., 2020, Sistla et al., 2013).



Figure 4. Schematic figure of plant feedback mechanisms on atmospheric warming (global warming). Positive and negative feedback mechanisms are represented by solid and hatched arrows, respectively. 1) indicates the process by which local soil shading by plants slows down permafrost thawing, resulting in decelerating warming. 2) indicates the process by which plants captures snow during winter leading to warmer soils that eventually cause shrub expansion and accelerated warming, due to permafrost thaw. 3) indicates the process in which albedo is reduced due plants emerging through the snow, leading to accelerated warming. And the process where albedo positively effects spring thaw, resulting in prolonged season of permafrost thawing. 4) indicates the process in which more carbon is stored as biomass in plants, causing less carbon to be present in the atmosphere which decelerates warming.

Conclusions

Arctic plant communities will experience a shift towards being taller when exposed to the predicted higher temperatures of a warmer future. Such height expansion in the arctic region will, in turn, entail several different feedback mechanisms, both positive and negative, on global climate. The interplay between the different positive and negative feedback mechanisms will determine whether the outcome of such feedback will mean a deceleration or acceleration of global warming, although it is likely that the main feedback systems are of positive character, which accelerates warming. Species abundance and composition will be key factors to understand future changes in arctic plant communities, and an increased understanding of which species that contributes the most to a specific functional trait within a community is needed to explain the variation. Finally, temperature alone is not enough trying to explain how arctic vegetation may change in the future. Moisture and nutrient availability must also be accounted for when predicting arctic plant communities in the future.

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References

Beringer, J., Chapin, F., Thompson, C., & McGuire, A. (2005). Surface energy exchanges along a tundra-forest transition and feedbacks to climate. *Agricultural and Forest Meteorology*, *131*(3), 143-161.

Bjorkman, A., Myers-Smith, I., Elmendorf, S., Ozinga, W., Sheremetev, B., Weiher, E., & Et al. (2018a). Plant functional trait change across a warming tundra biome. *Nature (London), 562*(7725), 57-62.

Bjorkman, A., Myers-Smith, I., Elmendorf, S., Normand, S., Thomas, H., Alexander, H., . . . Zamin, T. (2018b). Tundra Trait Team: A database of plant traits spanning the tundra biome. *Global Ecology and Biogeography, 27*(12), 1402-1411.

Bonfils, C., Phillips, T., Lawrence, D., Cameron-Smith, P., Riley, W., & Subin, Z. (2012). On the influence of shrub height and expansion on northern high latitude climate. *Environmental Research Letters*, *7*(1), 015503.

Blok, D., Heijmans, M., Schaepman-Strub, G., Kononov, A., Maximov, T., & Berendse, F. (2010). Shrub expansion may reduce summer permafrost thaw in Siberian tundra. *Global Change Biology*, *16*(4), 1296-1305.

Chapin, F., Sturm, M., Serreze, M., McFadden, J., Key, J., Lloyd, A., . . . Welker, J. (2005). Role of land-surface changes in Arctic summer warming. *Science (American Association for the Advancement of Science)*, *310*(5748), 657-660.

Criado, M., Myers-Smith, I., Bjorkman, A., Lehmann, C., & Stevens, N. (2020). Woody plant encroachment intensifies under climate change across tundra and savanna biomes. *Global Ecology And Biogeography, 2020, Vol. 29, Iss. 5, Pp. 925-.943, 29*(5), 925-943.

Elmendorf, S., Henry, G., Hollister, R., Björk, R., Boulanger-Lapointe, N., Cooper, E., . . . Wipf, S. (2012). Plot-scale evidence of tundra vegetation change and links to recent summer warming. *Nature Climate Change, 2012, Vol. 2, Iss. 6, Pp. 453-.457, 2*(6), 453-457.

Eskelinen, A., & Oksanen, J. (2006). Changes in the abundance, composition and species richness of mountain vegetation in relation to summer grazing by reindeer. *Journal of Vegetation Science*, *17*(2), 245-254.

Evans, RD. (2001) Physiological mechanisms influencing plant nitrogen isotope composition. *Trends in Plant Science, 6,* 121-126

Forbes, B.C., Fauria, M.M., and Zetterberg, P. (2010) Russian arctic warming and 'greening' are closely tracked by tundra shrub willows *Glob. Change Biol. 16* 1542–54

DeMarco, Jennie; Mack, Michelle C.; Bret-Harte, M. Syndonia (2014): Effects of arctic shrub expansion on biophysical vs. biogeochemical drivers of litter decomposition. *Ecology 95*(7), 1861-1875

Haagmans, V. J. (2021): Modelling the significance of snow-vegetation interactions for active layer dynamics in an Arctic permafrost region subjected to tundra shrubification, Master thesis, *Eidgenössische Technische Hochschule Zürich.*

Hudson, J., Henry, G., & Cornwell, W. (2011). Taller and larger: Shifts in Arctic tundra leaf traits after 16 years of experimental warming. *Global Change Biology*, *17*(2), 1013-1021.

IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Retrieved from <u>https://www.ipcc.ch/report/ar6/wg1/#FullReport</u>

Lawrence, D., & Swenson, S. (2011). Permafrost response to increasing Arctic shrub abundance depends on the relative influence of shrubs on local soil cooling versus large-scale climate warming. *Environmental Research Letters, 6*(4), 45504.

Mod, H., & Luoto, M. (2016). Arctic shrubification mediates the impacts of warming climate on changes to tundra vegetation. *Environmental Research Letters, 11*(12), 124028.

Myers-Smith, Forbes, Wilmking, Hallinger, Lantz, Blok, . . . Hik. (2011a). Shrub expansion in tundra ecosystems: Dynamics, impacts and research priorities. *Environmental Research Letters*, **6**, 15

Myers-Smith, I., Hik, D., Kennedy, C., Cooley, D., Johnstone, J., Kenney, A., & Krebs, C. (2011b). Expansion of Canopy-Forming Willows Over the Twentieth Century on Herschel Island, Yukon Territory, Canada. *Ambio*, *40*(6), 610-623.

Myers-Smith, I., & Hik, D. (2013). Shrub canopies influence soil temperatures but not nutrient dynamics: An experimental test of tundra snow–shrub interactions. *Ecology and Evolution, 3*(11), 3683-3700.

Myers-Smith, I., & Hik, D. (2015a). Shrub canopies influence soil temperatures but not nutrient dynamics: An experimental test of tundra snow–shrub interactions. *Ecology and Evolution*, *3*(11), 3683-3700.

Myers-Smith, I., Elmendorf, S., Beck, P., Wilmking, M., Hallinger, M., Blok, D., . . . Vellend, M. (2015b). Climate sensitivity of shrub growth across the tundra biome. *Nature Climate Change*, *5*(9), 887-891.

Myers-Smith, I., Thomas, H., & Bjorkman, A. (2019). Plant traits inform predictions of tundra responses to global change. *The New Phytologist, 221*(4), 1742-1748. Je4960

Moles, A. T., Warton, D. I., Warman, L., Swenson, N. G., Laffan, S. W., Zanne, A. E., ... Leishman, M. R. (2009). Global patterns in plant height. *Journal of Ecology, 97*, 923-932

Nauta, A., Heijmans, M., Blok, D., Limpens, J., Elberling, B., Gallagher, A., . . . Berendse, F. (2015). Permafrost collapse after shrub removal shifts tundra ecosystem to a methane source. *Nature Climate Change*, *5*(1), 67-70.

Pistone, K., Eisenman, I., & Ramanathan, V. (2014). Observational determination of albedo decrease caused by vanishing Arctic sea ice. *Proceedings of the National Academy of Sciences - PNAS, 111*(9), 3322-3326.

Pearson, R., Phillips, S., Loranty, M., Beck, P., Damoulas, T., Knight, S., & Goetz, S. (2013). Shifts in Arctic vegetation and associated feedbacks under climate change. *Nature Climate Change*, *3*(7), 673-677.

Pérez-Harguindeguy, N., Díaz, S., Garnier, E., Lavorel, S., Poorter, H., . . . Cornelissen, J.H. C. (2013). New handbook for standardised measurement of plant functional traits worldwide. *CSIRO*. Retrieved from the University of Minnesota Digital Conservancy, <u>https://hdl.handle.net/11299/177647</u>.

Perez-Ramos, Ignacio & Roumet, Catherine & Cruz, Pablo & Blanchard, Alain & Autran, Paul & Garnier, Eric. (2012). Evidence for a 'plant community economics spectrum' driven by nutrient and water limitations in a Mediterranean rangeland of southern France. Journal of Ecology. *100*, 1315-1327.

Post, E., Forchhammer, M., Bret-Harte, M., Callaghan, T., Christensen, T., Elberling, B., ... Aastrup, P. (2009). Ecological dynamics across the Arctic associated with recent climate change. *Science (American Association for the Advancement of Science), 325*(5946), 1355-1358.

Reich, P., Walters, M., & Ellsworth, D. (1992). Leaf life-span in relation to leaf, plant, and stand characteristics among diverse ecosystems. *Ecological Monographs, 62*(3), 365-392.

Rew, L., McDougall, K., Alexander, J., Daehler, C., Essl, F., Haider, S., ... Rabitsch, W. (2020). Moving up and over: Redistribution of plants in alpine, Arctic, and Antarctic ecosystems under global change. *Arctic, Antarctic, and Alpine Research, 52*(1), 651-665.

Saunois, M., R. Stavert, A., Poulter, B., Bousquet, P., G. Canadell, J., B. Jackson, R., . . . Zhuang, Q. (2020). The global methane budget 2000-2017. *Earth System Science Data, 12*(3), 1561-1623.

Scharn, R., Little, C., Bacon, C., Alatalo, J., Antonelli, A., Björkman, M., . . . Björk, R. (2021a). Decreased soil moisture due to warming drives phylogenetic diversity and community transitions in the tundra. *Environmental Research Letters, 16*(6), 64031.

Scharn, R., Brachmann, C., Patchett, A., Reese, H., Bjorkman, A., Alatalo, J., . . . Björkman, M. (2021b). Vegetation responses to 26 years of warming at Latnjajaure Field Station, northern Sweden. *Arctic Science*

Schuur, E., McGuire, A., Schädel, C., Grosse, G., Harden, J., Hayes, D., . . . Vonk, J. (2015). Climate change and the permafrost carbon feedback. *Nature (London), 520*(7546), 171-179.

Sistla, S., Moore, J., Simpson, R., Gough, L., Shaver, G., & Schimel, J. (2013). Long-term warming restructures Arctic tundra without changing net soil carbon storage. *Nature (London), 497*(7451), 615-617.

Sturm, Matthew; Holmgren, Jon; McFadden, Joseph P.; Liston, Glen E.; Chapin, F. Stuart; Racine, Charles H. (2001): Snow - shrub Interactions in Arctic Tundra: A Hypothesis with Climatic Implications. In J. Climate 14 (3), pp. 336±344. DOI: 10.1175/1520-0442(2001)0142.0.CO;2.

Sturm, M., Douglas, T., Racine, C., & Liston, G. (2005a). Changing snow and shrub conditions affect albedo with global implications. *Journal of Geophysical Research. Biogeosciences, 110*(G1), Journal of geophysical research. Biogeosciences, 2005-09-07, Vol.110 (G1).

Sturm, M., Schimel, J., Michaelson, G., Welker, J., Oberbauer, S., Liston, G., ... Romanovsky, V. (2005b). Winter biological processes could help convert Arctic tundra to shrubland. *Bioscience*, *55*(1), 17-26.

Suter, M., & Edwards, P. (2013). Convergent succession of plant communities is linked to species' functional traits. *Perspectives in Plant Ecology, Evolution and Systematics, 15*(4), 217-225.

Violle, C., Navas, M., Vile, D., Kazakou, E., Fortunel, C., Hummel, I., & Garnier, E. (2007). Let the Concept of Trait Be Functional. *Oikos, 116*(5), 882-892.

Vowles, T., Björk, R., & Prentice, H. (2019). Implications of evergreen shrub expansion in the Arctic. *The Journal of Ecology, 107*(2), 650-655.

Wager, H. (1938). Growth and Survival of Plants in the Arctic. *The Journal of Ecology, 26*(2), 390-410.

Wayne Polley, H., Yang, C., Wilsey, B., Fay, P., & He, K. (2020). Spectrally derived values of community leaf dry matter content link shifts in grassland composition with change in biomass production. Remote Sensing in Ecology and Conservation, 6(3), 344-353.

Wright, I., Reich, P., Westoby, M., Ackerly, D., Baruch, Z., Bongers, F., . . . Villar, R. (2004). The worldwide leaf economics spectrum. *Nature (London), 428*(6985), 821-827.

Zanzottera, M., Dalle Fratte, M., Caccianiga, M., Pierce, S., & Cerabolini, B. (2020). Community-level variation in plant functional traits and ecological strategies shapes habitat structure along succession gradients in alpine environment. *Community Ecology*, *21*(1), 55-65.

Appendix

1.1 Popular science report

ARCTIC PLANT COMMUNITIES RISE WITH TEMPERATURES

It is no news that temperatures are rising all over our planet. But did you know that it is most extreme in the arctic regions? The intergovernmental UN body, IPCC, reports that temperatures are increasing three times as fast in the arctic as the global average. The permanently frozen soils of the arctic is estimated to store half of the global soil carbon. If these permafrost soil layers where to thaw, exposing the stored carbon would lead to greenhouse gas emissions in the form of carbon dioxide and methane gas, accelerating the climate warming even further and changing our planet not least our arctic plant communities. Studying plant community changes of functional traits can provide information to what can be expected in the future for plant ecosystems of the arctic. This is necessary, not only to understand the effect of arctic ecosystems, but also for understanding future plant feedback mechanisms on climate change.

Vegetational changes

Studies in the arctic performed in the field and via satellite images show great changes in plant distribution. Species such as shrubs and grasses seem to benefit the most with warmer temperatures. Already existing plant species in the arctic are getting bigger, as well as an ongoing migration of larger plant species both upslope mountains and in latitudinal range. Less is known about traits regarding the so-called resource economics spectrum. Functional traits of the economic resource spectrum provide information of how well plants can endure harsh environments, which the situation in the arctic.





Plant functional traits are environmental factors that affect how plants look and function. These factors can be abiotic, such as temperature and pH, or biotic, such as grazing or competition.

What happens to arctic plant communities when exposed to warming?

Understanding how plant functional traits, vary within plant communities while being exposed to experimental warming is important to understand how plant communities will manage in a warmer future. Further, understanding the connection of differences in functional traits with feedback mechanisms towards global warming is also important to improve the knowledge of how variations in arctic vegetation affects global warming. One such functional trait is plant height, which is shown to increase in temperature manipulated compared to unmanipulated communities in Latnjajaure, an arctic region in northern Sweden.

What effects do taller plant communities have on global climate change?

When plant communities of the arctic changes it has a major impact on feedback mechanisms towards global climate warming. The two main positive feedbacks (positive meaning mechanisms that accelerates the temperature increase) is changing albedo and permafrost thawing. Albedo is the amount of solar radiation reflected to space. Tall plants reaching above the snow decreases the albedo, leading to more solar radiation being absorbed by the earth's surface, which increases the temperature. Permafrost store greenhouse gases, so increased thawing of permafrost due to increased soil temperatures as plant communities grow larger emits more gases, which also accelerates warming. One negative feedback, that decelerate global climate change, is plants storing carbon in their woody structures and thereby lowering the atmospheric carbon.

2.1 Output from t-test and ManWU Trait ~ Treatment

| | t (t-test) W (ManWU) | p-value |
|----------------------------|----------------------|---------|
| Abisko | | |
| 2012 | | |
| Height ~ Treatment | 35(W) | 0.9636 |
| Leaf area ~ Treatment | -0.73408 | 0.481 |
| SLA ~ Treatment | 0.64058 | 0.871 |
| LDMC ~ Treatment | 1.0763 | 0.306 |
| LeafN ~ Treatment | 27 (W) | 0.4371 |
| 2013 | | |
| Height ~ Treatment | -1.3202 | 0.232 |
| log(Leaf area) ~ Treatment | 0.73261 | 0.485 |
| SLA ~ Treatment | -1.7668 | 0.132 |
| LDMC ~ Treatment | -0.17944 | 0.862 |
| LeafN ~ Treatment | 0.38914 | 0.708 |
| Latnjajaure | | |
| 2013 | | |
| Height ~ Treatment | -2.476 | 0.0297* |
| Leaf area ~ Treatment | -0.4449 | 0.6609 |
| SLA ~ Treatment | -0.2506 | 0.8044 |
| LDMC ~ Treatment | 85.5 | 0.9795 |
| LeafN ~ Treatment | -1.5969 | 0.1255 |
| 2014 | | |
| log(Height) ~ Treatment | -0.5772 | 0.5705 |
| Leaf area ~ Treatment | 0.21047 | 0.8356 |
| SLA ~ Treatment | -0.21377 | 0.8329 |
| LDMC ~ Treatment | -0.65921 | 0.5182 |
| LeafN ~ Treatment | 1.6771 | 0.1099 |
| 2016 | | |
| log(Height) ~ Treatment | -2.1096 | 0.0409* |
| Leaf area ~ Treatment | 298 | 0.7878 |
| SLA ~ Treatment | -0.58168 | 0.5637 |
| LDMC ~ Treatment | 262 | 0.335 |
| LeafN ~ Treatment | 336 | 0.6581 |
| Kilpisjärvi | | |
| 2013 | | |
| log(Height) ~ Treatment | -0.6314 | 0.5465 |
| Leaf area ~ Treatment | -1.0855 | 0.3169 |
| SLA ~ Treatment | -1.2239 | 0.2562 |
| LDMC ~ Treatment | -1.1022 | 0.3026 |

| LeafN ~ Treatment | -0.1838 | 0.8599 |
|-----------------------|---------|--------|
| 2016 | | |
| Height ~ Treatment | -0.5708 | 0.5843 |
| Leaf area ~ Treatment | -0.5222 | 0.6161 |
| SLA ~ Treatment | -0.5210 | 0.6181 |
| LDMC ~ Treatment | 0.3597 | 0.7284 |
| LeafN ~ Treatment | 0.0872 | 0.9326 |
| 2019 | | |
| Height ~ Treatment | 9 | 0.5476 |
| Leaf area ~ Treatment | -0.3356 | 0.7460 |
| SLA ~ Treatment | -0.0081 | 0.9937 |
| LDMC ~ Treatment | 0.0362 | 0.9722 |
| LeafN ~ Treatment | -0.4675 | 0.6529 |

2.2 Linear model ANOVA output variance between trait ~treatment*year

| | Sum Squares | df | F | p value |
|------------------------------|-------------------------|----|-------|--------------------|
| Abisko | | | | |
| Height ~ Treatment Year | 1.08 • 10 ⁻³ | 1 | 0.95 | 0.338 |
| Height ~ Year | 1.75 • 10 ⁻⁴ | 1 | 0.15 | 0.698 |
| Leaf area ~ Treatment Year | 8.47 • 10 ³ | 1 | 0.75 | 0.394 |
| Leaf area ~ Year | 9.73 • 10 ³ | 1 | 8.64 | 0.007 |
| SLA ~ Treatment Year | 0.05 | 1 | 0.05 | 0.871 |
| SLA ~ Year | 12.46 | 1 | 12.46 | 0.013 |
| LDMC ~ Treatment Year | 4.97 • 10 ⁻⁴ | 1 | 2.20 | 0.150 |
| LDMC ~ Year | 2.62 • 10 ⁻³ | 1 | 11.63 | 0.002 |
| LeafN ~ Treatment Year | 5.35 | 1 | 2.11 | 0.159 |
| LeafN ~Year | 29.70 | 1 | 11.70 | 0.002 |
| Latnjajaure | | | | |
| Height ~ Treatment Year | 0.23 | 1 | 8.61 | 0.004* |
| Height ~ Year | 0.18 | 2 | 3.26 | 0.043 |
| Leaf area ~ Treatment Year | 1.50 • 10 ³ | 1 | 0.03 | 0.872 |
| Leaf area ~ Year | 4.19 • 10 ⁵ | 2 | 3.64 | 0.03 |
| SLA ~ Treatment Year | 1.84 | 1 | 0.3 | 0.582 |
| SLA ~ Year | 59.40 | 2 | 4.93 | 0.009 |
| LDMC ~ Treatment Year | 8.97 · 10 ⁻⁴ | 1 | 0.72 | 0.399 |
| LDMC ~ Year | 7.23 • 10 ⁻³ | 2 | 2.89 | 0.061 |
| LeafN ~ Treatment Year | 0.08 | 1 | 0.01 | 0.903 |
| LeafN ~Year | 40.56 | 2 | 4.00 | 0.022 |
| Kilpisjärvi | | | | |

| Height ~ Year1.26 · 10 ⁻³ 20.530.597Leaf area ~ Treatment Year1.16 · 10 ³ 11.390.250Leaf area ~ Year2.20 · 10 ³ 21.310.287SLA ~ Treatment Year2.8210.900.351SLA ~ Year0.8920.140.868LDMC ~ Treatment Year5.48 · 10 ⁻⁵ 10.590.451LDMC ~ Year0.1910.110.744LeafN ~ Treatment Year0.3520.100.902 | Height ~ Treatment Year | 2.79 • 10 ⁻³ | 1 | 2.33 | 0.139 |
|---|------------------------------|-------------------------|---|------|-------|
| Leaf area ~ Treatment Year $1.16 \cdot 10^3$ 1 1.39 0.250 Leaf area ~ Year $2.20 \cdot 10^3$ 2 1.31 0.287 SLA ~ Treatment Year 2.82 1 0.90 0.351 SLA ~ Year 0.89 2 0.14 0.868 LDMC ~ Treatment Year $5.48 \cdot 10^{-5}$ 1 0.59 0.451 LDMC ~ Year $3.35 \cdot 10^{-5}$ 2 0.18 0.837 LeafN ~ Treatment Year 0.19 1 0.11 0.744 | Height ~ Year | 1.26 • 10 ⁻³ | 2 | 0.53 | 0.597 |
| Leaf area ~ Year2.20 · 10321.310.287SLA ~ Treatment Year2.8210.900.351SLA ~ Year0.8920.140.868LDMC ~ Treatment Year5.48 · 10 -510.590.451LDMC ~ Year3.35 · 10 -520.180.837LeafN ~ Treatment Year0.1910.110.744LeafN ~ Year0.3520.100.902 | Leaf area ~ Treatment Year | 1.16 • 10 ³ | 1 | 1.39 | 0.250 |
| SLA ~ Treatment Year 2.82 1 0.90 0.351 SLA ~ Year 0.89 2 0.14 0.868 LDMC ~ Treatment Year 5.48 · 10 ⁻⁵ 1 0.59 0.451 LDMC ~ Year 3.35 · 10 ⁻⁵ 2 0.18 0.837 LeafN ~ Treatment Year 0.19 1 0.11 0.744 LeafN ~ Year 0.35 2 0.10 0.902 | Leaf area ~ Year | 2.20 • 10 ³ | 2 | 1.31 | 0.287 |
| SLA ~ Year 0.89 2 0.14 0.868 LDMC ~ Treatment Year 5.48 · 10 ⁻⁵ 1 0.59 0.451 LDMC ~ Year 3.35 · 10 ⁻⁵ 2 0.18 0.837 LeafN ~ Treatment Year 0.19 1 0.11 0.744 LeafN ~ Year 0.35 2 0.10 0.902 | SLA ~ Treatment Year | 2.82 | 1 | 0.90 | 0.351 |
| LDMC ~ Treatment Year5.48 · 10^{-5}10.590.451LDMC ~ Year3.35 · 10^{-5}20.180.837LeafN ~ Treatment Year0.1910.110.744LeafN ~ Year0.3520.100.902 | SLA ~ Year | 0.89 | 2 | 0.14 | 0.868 |
| LDMC ~ Year 3.35 · 10 ⁻⁵ 2 0.18 0.837 LeafN ~ Treatment Year 0.19 1 0.11 0.744 LeafN ~ Year 0.35 2 0.10 0.902 | LDMC ~ Treatment Year | 5.48 • 10 ⁻⁵ | 1 | 0.59 | 0.451 |
| LeafN ~ Treatment Year 0.19 1 0.11 0.744 LeafN ~ Year 0.35 2 0.10 0.902 | LDMC ~ Year | 3.35 • 10 ⁻⁵ | 2 | 0.18 | 0.837 |
| LeafN ~Year 0.35 2 0.10 0.902 | LeafN ~ Treatment Year | 0.19 | 1 | 0.11 | 0.744 |
| | LeafN ~Year | 0.35 | 2 | 0.10 | 0.902 |

2.3 Results from comparing mean values and CWM values for the functional trait height

| | t | df | Mean CWM | Mean Height Mean | p-value |
|---------------------------------------|--------|--------|-----------|---------------------|---------|
| Latnjajaure | | | | | |
| 2013 | | | | | |
| Height*Mean ~ Height*CWM | 2.1821 | 15.52 | 0.4686753 | 0.3474331 | 0.04485 |
| 2014 | | | | | |
| log(Height*Mean) ~ log(Height*CWM) | 1.1173 | 19.224 | -1.321673 | -1.502172 | 0.2776 |
| 2016 | | | | | |
| log(Height*Mean)~ log(Height*CWM) | 1.1493 | 43.525 | -1.066067 | -1.206673 | 0.2567 |