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„Idiosyncratic responses of arctic plants to changing snow melt dates"

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Idiosyncratic responses of arctic plants to changing snow melt dates

The Arctic is one of the ecosystems most affected by climate change and especially winter temperatures and precipitation sums are supposed to increase. Consequently, snow cover depth and duration, the most important drivers of growing season length in the high Arctic, will also change. Depending on the extent and temporal patterns of temperature and precipitation rise, and the associated partitioning of precipitation sums into rain and snow components, this may either entail a shortened or prolonged snow free period, respectively. These changes will likely have multiple effects on plant productivity and hence the availability of biomass for consumers. In this study, I try to assess how the growth and productivity of eight common high arctic plant species will respond to different predicted climate change scenarios by experimentally changing snowmelt dates. My results demonstrate considerable variation among species with idiosyncratic positive and negative responses of individual species to either accumulation or reduction of snow cover depth and duration. I conclude that generic predictions of effects of a changing snow pack on the productivity of arctic vegetation are hardly possible, at least if a climate change driven species turn-over in local community compositions is not accounted for.

Introduction

Snow cover duration and depth are the most important drivers of growing season length in the Arctic (Hülber et al. 2011; Körner 2003; Van Wijk et al. 2003; M. D. Walker et al. 1999; Wipf & Rixen 2010). They affect soil temperatures by the insulation of soil and vegetation and thereby microbial activity during winter, thus controlling nutrient availability and soil moisture especially in spring during the onset of plant growth (M. D. Walker et al. 1999; Wipf & Rixen 2010). Consequently, snow cover duration and depth also effect plant productivity (Körner 2003), and thus the carbon sink capacity of the arctic ecosystem (Starr et al. 2008). Moreover, changes in the amount of available plant biomass and temporal patterns of plant phenology may also have cascading effects on pollinators, herbivores, pathogens and pests (Wipf 2010). Indeed, arctic ecosystems are among those most affected by climate change (Stow et al. 2004; Wipf & Rixen 2010).

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On the one hand temperatures in the Arctic have increased almost twice as much as the global average and even four fold in winter time over the past century (Christensen et al. 2007). Until the end of the 21st century the Intergovernmental Panel on Climate Change (Christensen et al. 2007) predicts a potential further increase of 5°C (based on the A1B scenario), with the most pronounced warming during winter months and least changes in summer. Additionally, precipitation in the Norwegian Arctic has increased by 2.5% per decade during the last century (Førland & Hanssen-Bauer 2003) and it is assumed that it will increase by another 18% until the end of this century (Christensen et al. 2007), again with a peak during winter (Christensen et al. 2007; Førland & Hanssen-Bauer 2003; Wipf & Rixen 2010). In combination, these forthcoming changes of temperature and precipitation regimes will have a big impact on the arctic snow cover which is, however, not easily predictable because it strongly depends on how precipitation sums are distributed across the winter season and, in particular, the partitioning into snow and rain fractions (Førland & Hanssen-Bauer 2003). Depending on these factors, two possible scenarios and therefore implications of climate change on the snow cover are conceivable. (1) Due to rising temperatures especially in winter the fraction of precipitation falling as rain could increase and hence reduce the snow cover depth and duration; this scenario would lead to a longer growing season due to an earlier snowmelt (Hülber et al. 2006; Pop et al. 2000; Starr et al. 2000; Starr et al. 2008; Stow et al. 2004; Van Wijk et al. 2003; Wahren et al. 2005; Wipf 2010; Wipf & Rixen 2010). However, (2) temperatures might also remain low enough during periods of maximum snowfall to ensure that an increase of precipitation in winter leads to a thicker and longer lasting snow cover, and hence to a shortened growing season following a later snowmelt (Cooper et al. 2011; Mallik et al. 2011; Morgner et al. 2010; Wipf & Rixen 2010). Uncertainties about these alternative scenarios include that most predictions are given on a large scale for the Arctic and do not account for regional differences. Indeed, the climate of Svalbard differs from other high arctic localities in that it is influenced by the gulf stream resulting in relatively warm winters and cold summers (Førland & Hanssen-Bauer 2003; Mallik et al. 2011). Furthermore, changes in cloud cover could lead to a shorter or constant snow free period even with a reduced snow depth (Walsh et al. 1997) or a strong rise of spring temperatures could compensate for a deeper snow pack (Wipf & Rixen 2010).

As a corollary, any study of snow pack mediated climate change effects on arctic ecosystems should account for both of these alternative scenarios. In this study, I focus on the

consequences of a climate-driven change in growing season length on the productivity of selected plant species, and I use experimental treatments which cover a range from a very early snowmelt until a very late one. Only very few snow manipulation experiments that include both an early and a late snowmelt have been conducted and to my knowledge none focused on the influence of snow cover duration on the growth of a wider range of high arctic plants (Wipf & Rixen 2010). However, parts of other studies or such that were conducted in other ecosystems (e.g. alpine) allow for various assumptions on the impact of both snow pack scenarios on the productivity of high arctic plant species (Dorrepaal et al. 2003; Seastedt & Vaccaro 2001; Starr et al. 2008; Van der Wal et al. 2000; M. D. Walker et al. 1999; Wipf & Rixen 2010).

Especially results from studies in low arctic regions suggest an increase of NPP (net primary production) following a prolonged growing season (e.g. Euskirchen et al. 2009; Stow et al. 2004). However, Pop et al. (2000) suppose that some species might be unable to increase or might even decrease their growth in response to a temporally advanced onset of growing season into a thermally less favorable time of the year. Such an earlier advance could lead to (1) early tissue damage by spring frosts and cold winds after snowmelt since plants lose their frost hardiness during the onset of growth (Jonas et al. 2008; Pop et al. 2000; Torp et al. 2010; Wahren et al. 2005; Wipf et al. 2009; Wipf 2010); (2) reduced number of leaves because leaf set is determined in this stage (Marylin D. Walker et al. 1995); and (3) generally decelerate physiological processes by lower temperatures in spring compared to an onset of growth during the warmest days in summer time (Stow et al. 2004; Wipf & Rixen 2010).

On the contrary, delayed snowmelt is assumed to cause a decrease in plant size since the short growing season is likely to be one of the main constraints on biomass accumulation for high arctic plant species (Cooper et al. 2011; Wipf & Rixen 2010). Additionally, a deeper snow pack leads to colder soils after snowmelt (Mallik et al. 2011; Morgner et al. 2010; Scott & Rouse 1995) and is supposed to harm especially ridge species since they respire too much during winter time under a thicker snow pack and thus warmer soils (Wipf & Rixen 2010). On the other hand, a deeper and prolonged snow cover shelters plants from spring frosts and cold winds (see above), causes more soil moisture after melt out (Jonas et al. 2008; Mallik et al. 2011; Morgner et al. 2010; Scott & Rouse 1995; Wahren et al. 2005) and warmer soils in winter presumably fostering mineralization rates and improving nutrient availability in spring (DeMarco et al. 2011; Mallik et al. 2011; Morgner et al. 2010; Scott & Rouse 1995; Wahren

et al. 2005; Walsh et al. 1997). In addition, onset of plant growth falls in a climatically more suitable period (Wahren et al. 2005; Marylin D. Walker et al. 1995).

In face of these partly contradictory considerations, generic predictions of how an altered snow pack will affect arctic plant productivity remain difficult. In this study I consequently use a couple of common high arctic plant species from different life forms (graminoids, herbs, shrubs) and with different habitat associations (snowbeds, ridges) and explore how a delayed or earlier snowmelt, respectively, might affect their growth. More precisely, I want to assess (1) which environmental factor determines above-ground biomass accumulation of high arctic plants, (2) if the selected species accumulate different amounts of biomass under altered snow durations and depths, and (3) if they are are able to adapt their growth characteristics under different climate change scenarios and, particularly, if they are able to grow until senescence and might hence compensate for a delay in growing season onset by postponing biomass production towards later in the growth season.

Material and Methods

Experimental setup

The fieldwork was conducted in Adventdalen (78°10′N, 16°06′E), which is one of the larger valleys on the high arctic archipelago of Svalbard, Norway in summer 2011. The annual mean temperature at the close-by airport of Longyearbyen at the end of the same valley during the last ten years was -3.7°C, with a minimum of -13.5°C in March, a maximum of 7.2°C in July and an annual mean precipitation of 177 mm (Norwegian Meterological Institute).

The experimental setup is based on Morgner et al. (2010). In this study, I used nine of twelve existing snow fences (1.5 m tall and 6.2 m long) which were established in autumn 2006, distributed over an area of approximately 1.5 km x 2.5 km and grouped into blocks of three fences each (200 x 200 m) which are at least 500 m apart from each other to account for heterogeneity of the landscape. The fences were established perpendicular to the main winter wind direction leading from the glaciers towards the sea (easterly winds) so that snow transported by wind accumulates behind the fences due to turbulences. Behind each fence, two subplots of 75 x 75 cm were established: one in the area of the deepest snow (in the following named *increased*), and another one in the area of intermediate snow depth (in the following named *medium*), representing a climate scenario that predicts a delay of snowmelt and hence a shortened growing season. To account for a climate scenario that

predicts less snow in favor of rain and hence an earlier melt out I designated a subplot next to each fence on a small windblown ridge that melts out earlier naturally (in the following named *shallow*) and another one on which the snow was manually removed on 1. May (in the following named *removed*). In contrast to the other treatments *removed* subplots were newly established in autumn 2010. To compare those subplots with current conditions I also observed an unmodified subplot for each fence (in the following named *control*). Since not all treatments could be realized at each fence this experiment was based on a total of 37 subplots: four *removed*, eight *shallow*, nine *control*, seven *medium* and nine *increased*. The low number of *removed* subplots is due to problems with lost markings during wintertime, probably because of reindeer interactions.

Abiotic measurements

Subplots were observed every second day and were defined as snow free when 50% of their area had melted out. In each block (i.e. three fences) was one data logger installed on 4. September 2007 (Tiny Tag Plus 2, Gemini Data Loggers, UK) for each treatment (i.e. *removed*, *shallow*, *control*, *medium* and *increased*) which recorded soil temperatures hourly at approximately two centimeters below the soil surface. Daily average soil temperatures of each logger were used for the entire block. Daily average air temperatures at two meters above the ground were taken from the new weather station of the University Centre in Svalbard in Adventdalen (The University Centre on Svalbard) around six kilometers west of the study site in the same valley. From these measurements I calculated nine different temperature variables for each subplot, three from air and six from soil measurements (table 1): these variables represent either the number of days with a mean temperature above 0°C or the cumulative temperatures above this threshold since either melt out dates or the 1. May, i.e. the date on which the snow got shoveled away on *removed* subplots. In addition, I also calculated the number of days with a mean temperature above 5°C. The temperature sum, respectively number of days until the day of each growth measurement, was then matched with the recorded plant size.

Biotic measurements

All biotic measurements were based on the ITEX manual (Molau & Edlund 1996) and were conducted in weekly intervals (ranging from 13. June until 8. September 2011). For those

study species not mentioned in the ITEX manual I adapted protocols following those of similar species. I chose eight common target species for the study site including deciduous and evergreen shrubs, graminoids and perennial forbs, as well as snowbed and ridge species: *Alopecurus magellanicus*, *Bistorta vivipara*, *Cassiope tetragona*, *Dryas octopetala*, *Luzula arcuata subsp. confusa*, *Pedicularis hirsuta*, *Salix polaris* and *Stellaria crassipes*.

As soon as a subplot had melted out, or individuals of a given species were visible, one randomly chosen individual per species was selected. For *S.polaris* four individuals per subplot were chosen in order to make sure that each a female and a male specimen would be included in the study. Plant size was measured with an electronic caliper with an accuracy of one millimeter. Only photosynthetically active parts were taken into account. If the marked individual got lost due to grazing or other disturbances (e.g. wind) a new randomly chosen individual nearby was marked and observed from then on and treated as a replicate in order to avoid loss of data.

For every species different measures were applied according to their morphology (table 2). For *A.magellanicus*, *D.octopetala*, *L.confusa* and *S.polaris* the summed length of all leaves (in mm) excluding the petiole (where applicable) was used whereas (in case of *A.magellanicus* leaves were defined from ligule to leaf tip). For *B.vivipara* the length and width of each leaf was used to calculate the leaf areas as ellipses and single leaf values were then summed for each individual. For *P.hirsuta* and *S.crassipes*, plant length was measured from soil surface until the uppermost leaf. For *C.tetragona*, the growth increment of a shoot of the year was used since the insertion of the youngest leaf on the caulis is not easily visible.

The date of the onset of senescence of each species in each subplot was obtained from a parallel study (Semenchuk et al., unpublished) and was defined as the day when 50% of all individuals per species and subplot were senescent.

Statistical analyses

The data was analyzed with the R software (R Development Core Team 2011) using the packages nlme (Pinheiro et al. 2012) and lattice (Sarkar 2008). Since the data was collected in a hierarchically organized experimental set up, I used linear mixed-effects models (function *lme*) to analyze the effect of the treatments on (1) melt out dates, (2) the different temperature variables and on (3) the average growth of the species throughout the season. In order to evaluate the effect of the temperature variables on plant size, I fitted the models

with a second order polynomial predictor since plants do not grow continuously even though cumulative temperature sums or number of days above the given threshold are still increasing. I selected the minimal model by stepwise removal of higher order terms from the full until the Null model, and chose the model with the lowest AIC (Akaike Information Criterion). Potential heteroscedasticity was considered for as much grouping levels (i.e. block, fence, subplot, individual) as possible (i.e. parameter estimation algorithms converted). These analyses were repeated for each species separately.

To determine which temperature variable explains plant size best, an independent model was computed for each of the nine temperature variables and species based on the matched temperature values and plant sizes for each recorded date and the variable resulting in a model with lowest AIC was chosen. Maximum plant sizes were computed by the function *predict.lme* on the basis of the selected model. It should be noted that it was not possible to compute confidence intervals for plant peak sizes as there is currently no respective algorithm implemented in R. In order to assess if the species grew until the onset of senescence, empirical plant size peaks were identified in the data for every individual and compared to the senescence date of their subplot.

Results

Abiotic measurements

Melt out dates of all treatment subplots differed significantly from those of *control* subplots (table 3). *Shallow* subplots were snow free on the 30. May, on average, *control* on the 4. June, *medium* on the 12. June, *increased* on the 16. June, while snow was manually removed from *removed* subplots on the 1. May as described above. The onset of the snow free period varied thus by up to 46 days.

Positive air temperature sums (thawing degree temperatures, in the following TDT) was the temperature variable that explained plant size the best (lowest AIC) for all species except *Dryas octopetala*, but was still a highly significant predictor for this species, too (table 4). For consistency, I hence used TDT in all subsequent analyses. The TDT of individual subplots depend on melt out dates only because air temperatures were derived from one single weather station. Consequently, this variable varied across treatments in parallel to melt out dates except that *control* and *shallow* subplots did not differ significantly (table 5), most

probably because of low air temperatures in spring. However, none of the other variables calculated from my temperature measurement series was able to explain temporal plant growth patterns in a similarly consistent way across species.

Senescence

Most species (i.e. *Alopecurus magellanicus*, *Bistorta vivipara*, *D.octopetala*, *Luzula confusa*, *Salix polaris* and *Stellaria crassipes*) did not increase in plant size until the onset of their senescence. By contrast, about two thirds of the individuals of *Pedicularis hirsuta* were steadily growing over time in the treatments *shallow*, *control* and *medium* (table 6; treatment *increased* could not be analyzed for this species due to lack of data). Similarly, many individuals of *Cassiope tetragona* in *control*, *medium* and *increased* treatments grew until senescence, while individuals in the treatment *removed* hardly grew at all.

Growth patterns of individual species

Alopecurus magellanicus

All treatments increased the summed leaf lengths of *A.magellanicus* compared to *control* (table 7). However, differences were only significant for a slightly delayed melt out date (*medium*) where leaf lengths were higher by 50% compared to ambient conditions. The modeled maximal plant sizes range from 105 -168 mm. However, the maximum plant size in *medium* is only enlarged by 9%. Figure 1a demonstrates that plants in *medium* were able to compensate for later snowmelt by enhanced growth rates, i.e. higher biomass accumulation per unit of temperature than in other treatments. The required TDT to reach the peak sizes range between 322°C in *removed* and 363°C in *medium*.

Bistorta vivipara

The average sum of leaf areas of *B.vivipara* varied between 360.5 mm^2 in *control* and 704.8 mm^2 in *increased* (table 8). The leaf area increased significantly behind fences, by 95% and 66% in *increased* and *medium*, respectively. Individuals in *medium* grew faster and hence reached a higher peak size (+57% compared to ambient conditions) but were senescing faster as well (figure 1b). Immediately behind the fences, *B.vivipara* grew less rapidly, reached a slightly lower peak size (+40% compared to *control*) but senesced slower and was thus photosynthetically active until later in autumn. Consequently, individuals in *increased* areas reached their full size later in the growing season and at higher levels of TDT, and they preserved their maximum biomass for a longer period of time. In subplots melting out

earlier, the size of *B.vivipara* individuals did not significantly differ from those of *control* subplots, maximal plant sizes required about the same amount of temperature sums as well.

Cassiope tetragona

All treatments significantly decreased the annual shoot increment of *C.tetragona* (table 9). Averages ranged between 0.19 mm in *shallow* and 2.32 mm in *control* and peaks sizes between 0.16 mm (*shallow*) and 3.41 mm (*control*). Most individuals in *medium* and *shallow* subplots did not grow at all (figure 1c) reducing the average shoot increment by 82% and 92%, respectively, compared to *control* throughout the season. In *increased* (*removed*) subplots shoots of *C. tetragona* grew shorter by 36% (59%), on average, and the modeled maximum plant sizes were reduced by 57% (61%) compared to *control*.

Dryas octopetala

All treatments apart from *shallow* increased leaf lengths and peak sizes for *D.octopetala* (table 10). Averages ranged from 17.4 mm in *shallow* to 29.2 mm in *medium* and modeled maximal sizes from 21.3 mm to 38.5 mm, again in *shallow* and *medium*. The treatment effect was most pronounced in *medium* where plants grew 60% larger than in *control* and the estimated maximum plant size was enlarged by almost 75%, followed by individuals immediately behind the fences (increase of 38% in total leaf length, respectively 53% larger peak sizes), which grew the fastest after snowmelt (figure 1d). A very early snowmelt (*removed*) triggered a higher seasonal biomass accumulation, too (treatment effect of +28%), while peak size as well as timing and senescence were similar to increased snow conditions. By contrast, plant growth did not significantly differ among plants in *shallow* and *control* subplots.

Luzula confusa

Growth responses of *L.confusa* to the different treatments were rather inconsistent (table 11, figure 2a). Under a very early snowmelt (*removed*) average plant size was increased by 27% compared to *control*, whereas a moderately decreased snow pack (*shallow*) reduced the species' growth by almost the same extent (24%). In parallel, plants reached a 12% higher maximum leaf length in removed, but a 35% lower maximum in shallow subplots. Shortening the growing season did not affect the species' full-season leaf length significantly, although maximum values are higher (+17% in *medium* and +21% in *increased* compared to *control*). This discrepancy results from an enhanced growth after snowmelt (coupled with

higher TDT to reach full size: +21% in *medium* and +14% in *increased* compared to *control*) and faster senescence in the end of the season.

Pedicularis hirsuta

Earlier as well as later snowmelt had a negative effect on the average plant size of *P.hirsuta* which varied from 17.2 mm in *shallow* to 29.6 mm in *control*. However, differences were not significant for latest snowmelt dates (*increased*), probably because of scarcity of data from this treatment (table 12). The full-season plant size was decreased by 15% in *removed*, 42% in *shallow* and 19% in *medium*. The individuals in *removed* subplots had a peculiar temporal growth pattern: they grew rapidly in the beginning and kept approximately their size throughout the season, whereas plants in other treatments grew more steadily (figure 2b).

Salix polaris

Average sums of leaf lengths of *S.polaris* ranged between 10.8 mm in *increased* and 12.7 mm *shallow* and the modeled maximum between 10.5 mm in *increased* and 15.2 mm in *control*. Only a very late snowmelt had a significantly negative effect on the average plant size and reduced it by 11% compared to ambient conditions (31% in terms of maximum length; table 13). Under moderately longer snow conditions (*medium*) individuals were smaller during their early growth phases, but an accelerated growth later on was compensating for this disadvantage (figure 2c). Peak sizes were hence similar to those of *control* individuals, but plants required higher TDT sums to reach their maximum size (329.4 in *medium*, compared to 281.3 in *control*. An earlier snowmelt (*removed* and *shallow*) did not affect the species significantly.

Stellaria crassipes

The average plant size of *S.crassipes* decreased with a delayed and increased with an advanced snowmelt, although this trend was only significant for the intermediate treatments with a decrease of 49% in *medium* (3.5 mm) and an increase of 64% in *shallow* (11.3 mm) compared to *control* (table 14). The modeled plant peak sizes varied from 5.7 mm in *shallow* to 11.5 mm in *removed* and stand thus in contrast to the average sizes where the highest value was recorded in *shallow*. Furthermore, the modeled maximal sizes and TDT to reach this size suggest that individuals in the treatments *removed* and *medium* grew until senescence, although they did not actually do so according to the phonological data. The

modeled growth shown in figure 2d is, however, based on relatively few measurements and hence does not allow for strong inferences.

Table 1 Overview of the nine calculated temperature variables based on daily average temperatures. Melt out dates were recorded for each subplot.

Air or soil temperature	Beginning of record	Threshold	Used value
Air	Melt out date	0°C	Temperature in °C
Air	Melt out date	0°C	Number of days
Air	Melt out date	5°C	Number of days
Soil	Melt out date	0°C	Temperature in °C
Soil	Melt out date	0°C	Number of days
Soil	Melt out date	5°C	Number of days
Soil	1. May	0°C	Temperature in °C
Soil	1. May	0°C	Number of days
soil	1. May	5°C	Number of days

Table 2 Overview of the species specific parameters per individual, growth form and habitat association

Species	Species specific parameter	Growth form	Habitat association
Alopecurus magellanicus	Sum of leaf lengths (from ligule to leaf tip)	Graminoid	Snowbed
Bistorta vivipara	Sum of leaf areas (calculated as ellipse based on leaf length and width)	Forb	Snowbed
Cassiope tetragona	Annual increment of one shoot	Evergreen shrub	Snowbed
Dryas octopetala	Sum of leaf lengths of one shoot (excluding petiole)	Evergreen shrub	Ridge
Luzula confusa	Sum of leaf lengths (from soil surface to leaf tip)	Graminoid	Ridge
Pedicularis hirsuta	Plant length (from soil surface to uppermost leaf)	Forb	Snowbed
Salix polaris	Sum of leaf lengths of one shoot (excluding petiole)	Deciduous shrub	Snowbed
Stellaria crassipes	Plant length (from soil surface to uppermost leaf)	Forb	Ridge

Table 3 Estimates of treatment effects on melt out dates in days of year (doy). Effect values other than the intercept (here control treatment) are deviations from the latter. Control= unmanipulated snow cover; removed= snow removal on 1. May; shallow= naturally early snowmelt; medium= intermediately increased snow; increased= maximally increased snow. Given are standard deviation (sd), t- and p-values and degrees of freedom (df) of the model.

	Effect ± sd	t-value	p-value
Intercept (Control)	155 ± 1.0		
Removed	-34 ± 0.9	-39.9	< 0.001
Shallow	-5 ± 0.7	-6.9	< 0.001
Medium	8 ± 0.6	14.1	< 0.001
Increased	12 ± 0.5	26.2	< 0.001
df	182		

Table 4 Estimates of the unimodal effect of TDT (thawing degree temperatures, i.e. sum of positive air temperatures) on plant size (in mm) of each recorded species throughout the season; effect sizes are given in °C. Given are standard deviations (sd), t- and p-values and degrees of freedom (df) of each model.

	Alopecurus magellanicus			*Bistorta vivipara*			*Cassiope tetragona*		
	Effect ± sd	t-value	p-value	Effect ± sd	t-value	p-value	Effect ± sd	t-value	p-value
(Intercept)	97.7 ± 9.0			399.7 ± 42.8			0.89 ± 0.25		
TDT linear	137.7 ± 13.4	10.25	< 0.001	299.8 ± 100.3	2.99	0.003	5.13 ± 0.87	5.89	< 0.001
TDT non-linear	-249.1 ± 4.4	-56.19	< 0.001	-2041.2 ± 40.1	-50.9	< 0.001	-2.82 ± 0.81	-3.47	< 0.001
df	154			256			165		

	Dryas octopetala			*Luzula confusa*			*Pedicularis hirsuta*		
	Effect ± sd	t-value	p-value	Effect ± sd	t-value	p-value	Effect ± sd	t-value	p-value
(Intercept)	20.3 ± 1.1			75.4 ± 6.6			23.9 ± 1.4		
TDT linear	81.3 ± 2.8	28.72	< 0.001	-187.4 ± 21.1	-8.86	< 0.001	66.9 ± 3.4	19.61	< 0.001
TDT non-linear	-48.3 ± 1.0	-46.98	< 0.001	-455.1 ± 7.0	-64.63	< 0.001	-22.7 ± 3.2	-7.17	< 0.001
df	244			228			145		

	Salix polaris			*Stellaria crassipes*		
	Effect ± sd	t-value	p-value	Effect ± sd	t-value	p-value
(Intercept)	11.3 ± 0.5			4.6 ± 0.6		
TDT linear	27.6 ± 3.8	7.34	< 0.001	24.6 ± 1.6	15.61	< 0.001
TDT non-linear	-65.3 ± 3.4	-19.46	< 0.001	-7.3 ± 1.3	-5.61	< 0.001
df	860			180		

Table 5 Estimates of treatment effects on TDT (thawing degree temperatures, i.e. positive air temperature sums in °C). Effect values other than the intercept (here control treatment) are deviations from the latter. Control= unmanipulated snow cover; removed= snow removal on 1. May; shallow= naturally early snowmelt; medium= intermediately increased snow; increased= maximally increased snow. Given are standard deviation (sd), t- and p-value and degrees of freedom (df) of the model.

	Effect ± sd	t-value	p-value
Intercept (Control)	272.7 ± 6.7		
Removed	45.7 ± 11.6	3.95	0.003
Shallow	10.7 ± 9.3	1.16	0.253
Medium	-26.4 ± 9.6	-2.74	0.009
Increased	-38.9 ± 9.0	-4.35	< 0.001
df	6180		

Table 6 Proportion of individuals per species and treatment that increased in size until senescence. Senescence was defined at the subplot level, namely as the day at which 50% of the subplot-population of a species were senescent. Control= unmanipulated snow cover; removed= snow removal on 1. May; shallow= naturally early snowmelt; medium= intermediately increased snow; increased= maximally increased snow. NA: no growth peak could be detected.

	Alopecurus magellanicus	*Bistorta vivipara*	*Cassiope tetragona*	*Dryas octopetala*	*Luzula confusa*	*Pedicularis hirsuta*	*Salix polaris*	*Stellaria crassipes*
Removed	0	0	0	0.17	0	0.25	0.09	0
Shallow	0	0	NA	0.6	0.29	0.75	0.12	0.25
Control	0.11	0	0.67	0.6	0	1	0.17	0.13
Medium	0	0.11	1	0.25	0.14	1	0.16	0
Increased	0	0.1	0.75	0.43	0.1	NA	0.06	NA

Table 7 Estimates of treatment effects on the average sum of leaf lengths of *Alopecurus magellanicus* (in mm) throughout the growing season. Effect values other than the intercept (here control treatment) are deviations from the latter. Given are standard deviation (sd), t- and p-value and degrees of freedom (df) of the model. Modeled maximal plant sizes and TDT (thawing degree temperatures, i.e. positive air temperature sums in °C) to reach the maximum size are based on the model shown in table 3. Control= unmanipulated snow cover; removed= snow removal on 1. May; shallow= naturally early snowmelt; medium= intermediately increased snow; increased= maximally increased snow.

	Effect ± sd	t-value	p-value	Peak size	TDT peak
Intercept (Control)	84.4 ± 11.4	7.43		112.9	334.0
Removed	14.1 ± 13.3	1.06	0.291	104.5	322.4
Shallow	15.2 ± 10.4	1.45	0.148	137.2	345.2
Medium	42.1 ± 9.9	4.25	< 0.001	168.4	362.8
Increased	19.1 ± 10.0	1.91	0.058	127.0	334.9
df	173				

Table 8 Estimates of treatment effects on the average sum of leaf areas of *Bistorta vivipara* (in mm^2) throughout the growing season. Effect values other than the intercept (here control treatment) are deviations from the latter. Given are standard deviation (sd), t- and p-value and degrees of freedom (df) of the model. Modeled maximal plant sizes and TDT (thawing degree temperatures, i.e. positive air temperature sums in °C) to reach the maximum size are based on the model shown in table 3. Control= unmanipulated snow cover; removed= snow removal on 1. May; shallow= naturally early snowmelt; medium= intermediately increased snow; increased= maximally increased snow.

	Effect ± sd	t-value	p-value	Peak size	TDT peak
Intercept (Control)	360.5 ± 60.6	5.94		505.4	296.0
Removed	23.8 ± 73.0	0.33	0.745	489.1	280.2
Shallow	11.3 ± 63.7	0.18	0.859	471.6	271.9
Medium	238.3 ± 63.2	3.77	< 0.001	793.1	297.6
Increased	344.3 ± 60.0	5.73	< 0.001	705.1	370.1
df	295				

Table 9 Estimates treatment effects on the average annual shoot increment of *Cassiope tetragona* (in mm) throughout the growing season. Effect values other than the intercept (here control treatment) are deviations from the latter. Given are standard deviation (sd), t- and p-value and degrees of freedom (df) of the model. Modeled maximal plant sizes and TDT (thawing degree temperatures, i.e. positive air temperature sums in °C) to reach the maximum size are based on the model shown in table 3. Control= unmanipulated snow cover; removed= snow removal on 1. May; shallow= naturally early snowmelt; medium= intermediately increased snow; increased= maximally increased snow.

	Effect ± sd	t-value	p-value	Peak size	TDT peak
Intercept (Control)	2.32 ± 0.29	8.09		3.41	419.6
Removed	-1.37 ± 0.39	-3.53	< 0.001	1.34	466.7
Shallow	-2.13 ± 0.31	-6.78	< 0.001	0.16	0.0
Medium	-1.89 ± 0.32	-5.93	< 0.001	0.18	295.1
Increased	-0.84 ± 0.29	-2.91	0.004	1.47	494.9
df	177				

Table 10 Estimates of treatment effects on the average sum of leaf lengths of *Dryas octopetala* (in mm) throughout the growing season. Effect values other than the intercept (here control treatment) are deviations from the latter. Given are standard deviation (sd), t- and p-value and degrees of freedom (df) of the model. Modeled maximal plant sizes and TDT (thawing degree temperatures, i.e. positive air temperature sums in °C) to reach the maximum size are based on the model shown in table 3. Control= unmanipulated snow cover; removed= snow removal on 1. May; shallow= naturally early snowmelt; medium= intermediately increased snow; increased= maximally increased snow.

	Effect ± sd	t-value	p-value	Peak size	TDT peak
Intercept (Control)	18.2 ± 2.2			22.2	410.2
Removed	5.1 ± 2.0	2.51	0.013	31.3	570.0
Shallow	-0.8 ± 1.7	-0.45	0.653	21.3	399.0
Medium	11.0 ± 1.9	5.96	< 0.001	38.5	542.0
Increased	6.9 ± 1.9	3.69	< 0.001	33.9	497.6
df	288				

Table 11 Estimates of treatment effects on the average sum of leaf lengths of *Luzula confusa* (in mm) throughout the growing season. Effect values other than the intercept (here control treatment) are deviations from the latter. Given are standard deviation (sd), t- and p-value and degrees of freedom (df) of the model. Modeled maximal plant sizes and TDT (thawing degree temperatures, i.e. positive air temperature sums in °C) to reach the maximum size are based on the model shown in table 3. Control= unmanipulated snow cover; removed= snow removal on 1. May; shallow= naturally early snowmelt; medium= intermediately increased snow; increased= maximally increased snow.

	Effect ± sd	t-value	p-value	Peak size	TDT peak
Intercept (Control)	77.4 ± 10.9			108.9	236.6
Removed	20.5 ± 8.7	2.35	0.020	122.0	240.1
Shallow	-23.8 ± 7.1	-3.37	< 0.001	71.0	248.5
Medium	-7.9 ± 7.6	-1.05	0.297	127.7	287.1
Increased	11.2 ± 7.0	1.60	0.112	131.9	269.0
df	261				

Table 12 Estimates of treatment effects on the average plant sizes of *Pedicularis hirsuta* (in mm) throughout the growing season. Effect values other than the intercept (here control treatment) are deviations from the latter. Given are standard deviation (sd), t- and p-value and degrees of freedom (df) of the model. Modeled maximal plant sizes and TDT (thawing degree temperatures, i.e. positive air temperature sums in °C) to reach the maximum size are based on the model shown in table 3. Control= unmanipulated snow cover; removed= snow removal on 1. May; shallow= naturally early snowmelt; medium= intermediately increased snow; increased= maximally increased snow.

	Effect ± sd	t-value	p-value	Peak size	TDT peak
Intercept (Control)	29.6 ± 2.2			34.9	526.6
Removed	-4.5 ± 1.8	-2.46	0.016	22.0	413.3
Shallow	-12.4 ± 1.5	-8.02	< 0.001	22.6	520.8
Medium	-5.7 ± 1.9	-3.04	0.003	31.3	428.8
Increased	-0.4 ± 2.2	-0.17	0.867	47.0	570.0
df	112				

Table 13 Estimates of treatment effects on the average sum of leaf lengths of *Salix polaris* (in mm) throughout the growing season. Effect values other than the intercept (here control treatment) are deviations from the latter. Given are standard deviation (sd), t- and p-value and degrees of freedom (df) of the model. Modeled maximal plant sizes and TDT (thawing degree temperatures, i.e. positive air temperature sums in °C) to reach the maximum size are based on the model shown in table 3. Control= unmanipulated snow cover; removed= snow removal on 1. May; shallow= naturally early snowmelt; medium= intermediately increased snow; increased= maximally increased snow.

	Effect ± sd	t-value	p-value	Peak size	TDT peak
Intercept (Control)	12.1 ± 0.7			15.2	281.3
Removed	0.3 ± 0.7	0.51	0.611	14.1	283.0
Shallow	0.6 ± 0.6	1.08	0.283	14.8	280.3
Medium	-0.2 ± 0.6	-0.40	0.693	13.9	329.4
Increased	-1.3 ± 0.6	-2.34	0.020	10.5	296.2
df	324				

Table 14 Estimates of treatment effects on the average plant size of *Stellaria crassipes* (in mm) throughout the growing season. Effect values other than the intercept (here control treatment) are deviations from the latter. Given are standard deviation (sd), t- and p-value and degrees of freedom (df) of the model. Modeled maximal plant sizes and TDT (thawing degree temperatures, i.e. positive air temperature sums in °C) to reach the maximum size are based on the model shown in table 3. Control= unmanipulated snow cover; removed= snow removal on 1. May; shallow= naturally early snowmelt; medium= intermediately increased snow; increased= maximally increased snow.

	Effect + sd	t-value	p-value	Peak size	TDT peak
Intercept (Control)	6.9 ± 1.4			10.9	515.7
Removed	3.1 ± 1.9	1.60	0.112	11.5	570.0
Shallow	4.4 ± 1.9	2.36	0.020	5.7	489.9
Medium	-3.4 ± 1.7	-1.98	0.050	7.2	570.0
Increased	-1.8 ± 2.0	-0.89	0.373	10.0	570.0
df	148				
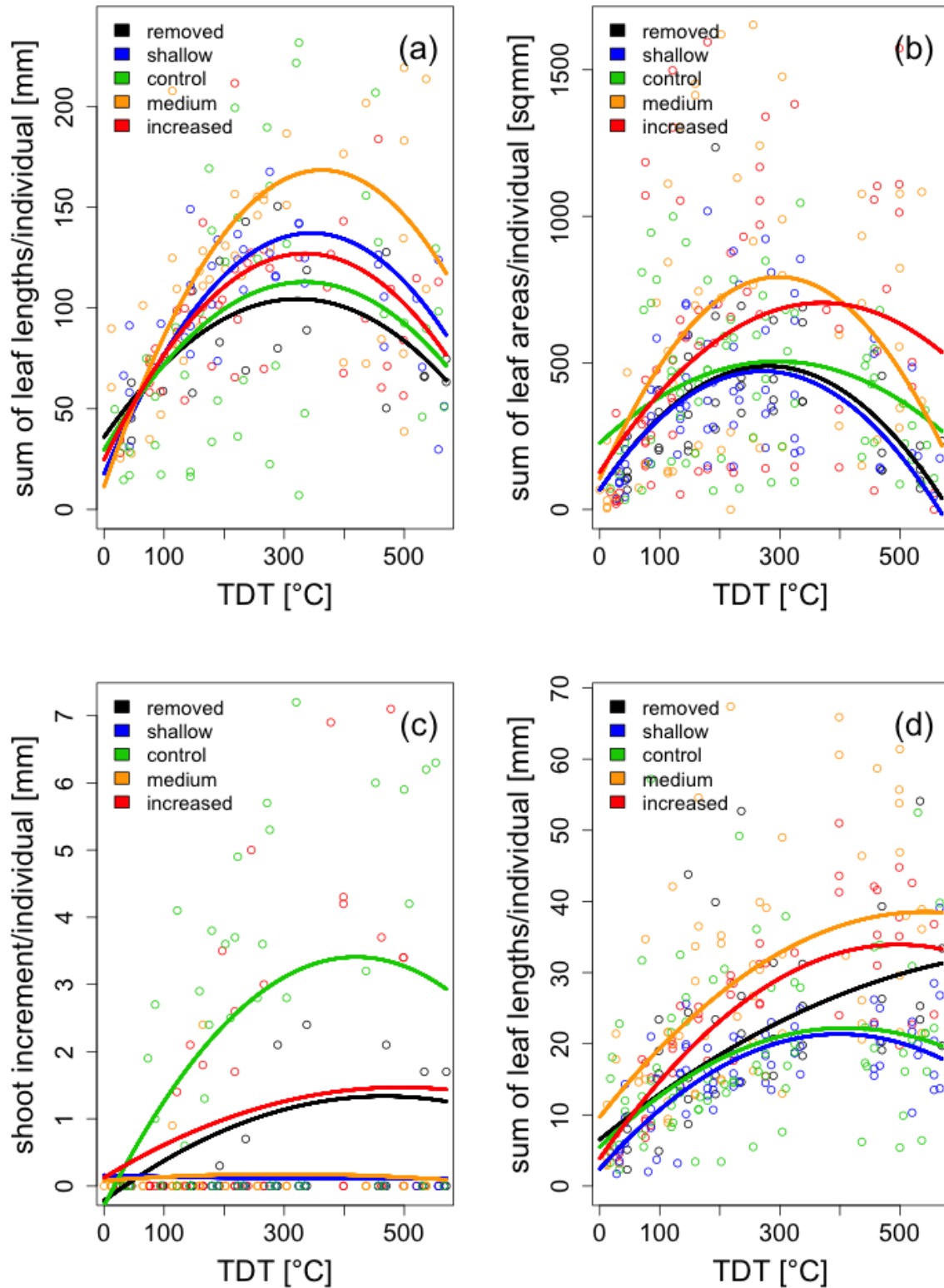
Figure 1 Relationship between TDT (cumulative sum of thawing degree temperatures, i.e. positive air temperature sums) and a) the average sum of leaf lengths of all *Alopecurus magellanicus* individuals; b) the average sum of leaf areas of all *Bistorta vivipara* individuals; c) the average shoot increment of all *Cassiope tetragona* individuals; d) the average sum of leaf lengths of all *Dryas octopetala* individuals. Coefficients are derived from a quadratic linear mixed-effect model, separated by treatments. Control= unmanipulated snow cover; removed= snow removal on 1. May; shallow= naturally early snowmelt; medium= intermediately increased snow; increased= maximally increased snow. Outliers are not shown for better visualization.
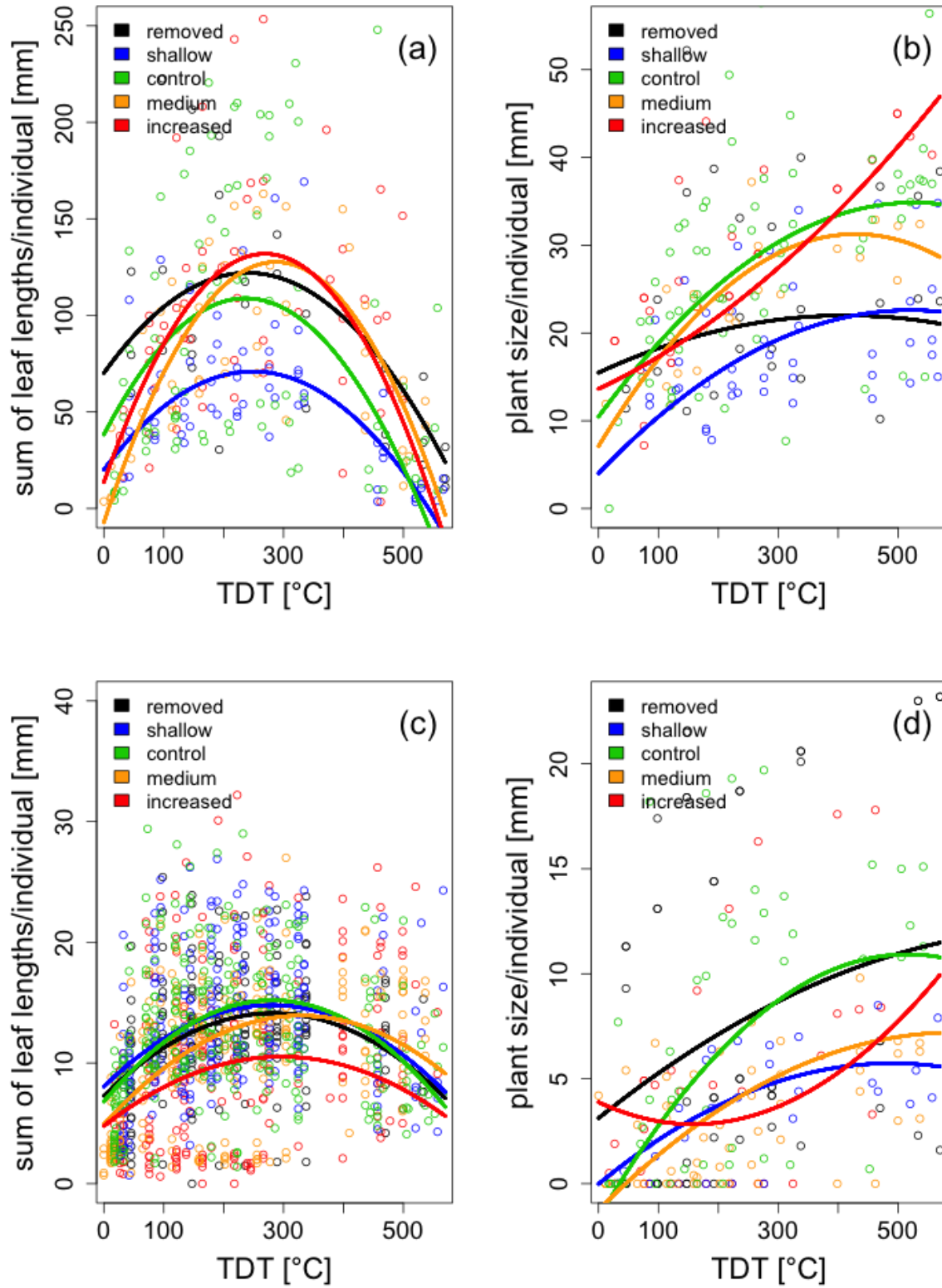
Figure 2 Relationship between TDT (cumulative sum of thawing degree temperatures, i.e. positive air temperature sums) and a) the average sum of leaf lengths of all *Luzula confusa* individuals; b) the average plant size of all *Pedicularis hirsuta* individuals; c) the average sum of leaf lengths of all *Salix polaris* individuals; d) the average plant size of all *Stellaria crassipes* individuals. Coefficients are derived from a quadratic linear mixed-effect model, separated by treatments. Control= unmanipulated snow cover; removed= snow removal on 1. May; shallow= naturally early snowmelt; medium= intermediately increased snow; increased= maximally increased snow. Outliers are not shown for better visualization.

Discussion

Abiotic measurements

Above-ground growth of the selected species is more closely correlated to air than to soil temperatures (cf. Walker et al. 1995 for a similar, but Wijk et al. 2003 for a contrasting result), with positive cumulative temperatures since snowmelt being the most significant predictor overall. This result suggests that it might be sufficient to use data from a close-by weather station and the use of data loggers at the field site is not strictly necessary which implies a reduction of work labor and finances for future studies. However, it is unsurprising that cumulative temperature sums are explaining plant growth better than simple melt out dates, and that a variable that includes both types of information is still more closely correlated to the productivity of arctic plants. Furthermore are sums of temperature values more accurate than number of days above a given threshold and it is not surprising that I found a better correlation for the first. This implies that the size of the observed species did not only depend on the length of the thawing period but also increased with higher temperatures.

Senescence

Only in case of *Cassiope tetragona* and *Pedicularis hirsuta* was a majority of the experimental plants able to continue their growth until they reached senescence under most treatments. This fits well together with the background that *C. tetragona* is a snow bed species (Lindner & Meister 2006; Rønning et al. 1996). There is a similar trend for *P.hirsuta*, except that the gradient is not that extreme for this species. It might be that the ability to grow until the onset of senescence depends on the environmental signal that triggers senescence with a photoperiodic trigger (the ratio of red to far red light) allowing less flexibility than a primary response to the annually varying weather conditions at the end of the growing season. All other species (*Alopecurus magellanicus*, *Bistorta vivipara*, *Dryas octopetala*, *Luzula confusa*, *Salix polaris* and *Stellaria crassipes*) were not able to grow until the onset of senescence and were thus not able to compensate a later melt out by extending the growth period into the autumn. Under a respective climatic scenario, plant biomass from these species would therefore become available later in spring/summer and for an overall shorter period of time which might have major implications for herbivores.

Further implications of snow manipulations

Even though soil moisture was not recorded in this study, Morgner et al. (2010) showed that it was increased by 50-80% at the beginning of the growing season behind fences at the same study site and I observed problems with water influx from the surroundings into *removed* subplots, which resulted in a higher moisture content into experimental plots at the beginning of the growth period compared to a scenario of area-wide earlier snowmelt. Moreover snow fences can trap wind-drifted litter and hence increase nutrient input behind them (Fahnestock et al. 2000; Wahren et al. 2005). Indeed, the accumulation of litter biomass behind comparable snow fences was recorded to be up to ten times higher by an increase of snow depth of two meters in Alaska (Fahnestock et al. 2000) and up to 30% of the nitrogen input derives from inorganic nitrogen that comes from snow (Walsh et al. 1997). Since arctic ecosystems are nutrient limited (Fahnestock et al. 2000; Starr et al. 2008; Wahren et al. 2005; Walsh et al. 1997) this implies an artificial trade-off between a shortened growing season and a higher nutrient input behind fences which probably co-determines the effects that the *medium* and *increased* treatments had on the different plant species in my study. By contrast, plants might be less able to profit from the extended growing season (e.g. in *shallow*) because this is the only treatment where neither soil moisture nor nutrient input were increased in parallel with the snow length manipulation. However, the nutrient input is in fact likely to increase by a prolonged growing season due to a gain of shrubs and thus litter deposition by rising temperatures.

Effects on plant size

Graminoids tend to respond particularly pronounced to nutrient input into nutrient-limited ecosystems (Wookey et al. 1995) and *Alopecurus magellanicus* in particular is known to perform best in moist habitats (Lindner & Meister 2006; Rønning et al. 1996) . Both of these factors probably explain the higher productivity of this species in *medium* subplots. However, since the effect of the *increased* treatment on the average sum of its leaf lengths was not significant, the performance of *A.magellanicus* illustrates the hypothesized trade-off between a shortened growing season and increased moisture and nutrient input behind fences inasmuch as the species' ability to benefit from the latter changes is obviously limited by the time available for biomass production. Given that at least local nutrient enrichment will be less pronounced under an area-wider higher and longer lasting snow pack, I conclude that *A. magellanicus* might possibly profit from a climate scenario that predicts a moderate

increase of snow cover at most, but will rather decline under both a more pronounced shortening of the growing season and an advance of snowmelt.

My result that the leaf areas of *Bistorta vivipara* are enlarged behind fences matches with the findings of Rønning et al. (1996) and Wookey et al. (1994) that this species has an enhanced growth on nutrient-rich sites and in years with an increased snow cover (Marylin D. Walker et al. 1995). The extensive increase of leaf area (95% in *increased* and 66% in *medium*) backs up the assumption that forbs respond more rapidly to changed environmental conditions than other life forms (Wahren et al. 2005). However, *B. vivipara* is a widespread and variable species (Wookey et al. 1994) and the result of only one species cannot be generalized for a whole life form. On the other hand, indifference of the species against earlier melt out matches with the results of Walker et al. (1995) and Starr et al. (2000) for the closely related *Bistorta bistortoides*. Walker et al. (1995) proposed that the initial growth falls in a period when temperatures are low, i.e. determination of the leaf set is determined during unsuitable climatic conditions resulting in a trade off with the longer growing season and no overall net effect in leaf areas. In summary, *B.vivipara* will possibly benefit from increased snowfall during winter, but will probably not take advantage from an earlier melt out.

Cassiope tetragona showed a smaller shoot increment in average and peak sizes in all treatments compared to *control*. One reason might be that evergreen shrubs follow a strategy of holding physiological activity at a constantly low level and are thus not adapting fast to any changes (Starr et al. 2008). This is in line with the results of an earlier study conducted at the same field site demonstrating a similar reduction of *Cassiope*-productivity behind fences (Mallik et al. 2011). The lack of positive response to fence treatments also suggests that this species is not limited by nutrients in the Arctic (Havström et al. 1993; Lindner & Meister 2006) and the reduction of growing season length due to an increased snow pack hence does not involve any positive side-effect for this species. Reduced growth under an earlier snowmelt contradicts the findings of Havström et al. (1993), probably because temperatures are the most limiting factor for this species in the Arctic (Havström et al. 1993; Lindner & Meister 2006) and plants might have been more exposed to spring frosts and winds in the *removed* and *shallow* treatments. Even though the analysis of the phenological data showed that *C.tetragona* is able to extend its growth until senescence, it is not able to benefit that much to reach the same productivity as under ambient conditions.

Dryas octopetala is supposed to grow better on dry localities with an early snowmelt like windblown ridges (Fahnestock et al. 2000; Lindner & Meister 2006; Morgner et al. 2010; Rønning et al. 1996) and is chionophobus (Morgner et al. 2010). Furthermore, Morgner et al. (2010) did not find a fence effect on its biomass at the same field site and Wookey et al. (1995) observed no significant effect of increased moisture on the same performance measure. By contrast, in my study the species increased its summed leaf lengths in the treatments *increased*, *medium* and *removed*, while I could not detect any significant response at the *shallow* subplots. My results are thus incongruent with the species' established habitat requirements. I therefore assume that the effect of the higher nutrient input behind fences and by water influx in *removed* (with nutrient influx as a side-effect) is sufficient to compensate for the disadvantages in these areas, since this effect was as well experimentally shown in Wookey et al. (1995). I conclude that *D.octopetala* might actually benefit from a thicker and prolonged snow cover due to a higher nutrient input, although part of this fertilization affect is, as already stated, probably an artifact of fences and local snow removal.

The results for *Luzula confusa* are fairly contradictory to the botanical literature for Svalbard which states dry and stony locations like windy ridges as its habitat and low nutrient requirements (Lindner & Meister 2006; Rønning et al. 1996). In addition, Van der Waal et al. (2000) found a higher quantity and size of leaves in areas with an advanced snowmelt for this species. In my study, by contrast, the leaf lengths were shorter on *shallow* subplots by about one quarter but longer by about the same amount on *removed* subplots. The latter increase might again have been driven by nutrient and moisture input at the removal plots which allowed the species to translate the longer growing season into increased productivity. The effect of a shortened snow free period is not significant in terms of whole-season biomass production. However, the model suggests that individuals behind fences have a differential temporal growth pattern inasmuch as they are able to compensate reduced growth rates early in the season by an accelerated growth later on which finally results in greater plant peak sizes. Van der Waal et al. (2000) found higher leaf qualities in delayed subplots, which suggests that *L.confusa* takes an advantage of the higher nutrient availability behind fences, like most graminoids do (Wookey et al. 1995), but this advantage does not enable the species to overcompensate the effect of a shorter growing season. In summary, my results suggest that *L.confusa* is not impaired by a shortened growing season

but does not benefit from it neither, whereas I suppose that its size might be reduced by an advanced snowmelt.

The unspecific semi-parasitic *Pedicularis hirsuta* prefers moist habitats with a continuous snow cover in winter like snow beds (Lindner & Meister 2006; Rønning et al. 1996). This is in line with my finding of a decreased plant size in *removed* and in *shallow* plots characterized by earlier melt out and drier soils during summer. Since those windblown ridges get snow free earlier and are supposed to be drier throughout the season. Growth reduction under a moderately increased snow pack (*medium*) might be due to a shorter growing season which is not balanced by an increased nutrient supply since *P.hirsuta* receives nutrients and water from its host plant. As stated above should the results in the treatment *increased* not be considered due to a lack of data. I assume therefore that this species will not benefit from any climate change even though it is able to extend its growth until the onset of senescence and is in contrast to my hypothesis not adapting well to a change of environmental.

I found no treatment effects on the leaf lengths of *Salix polaris* except for *increased* subplots where the species' productivity decreased. Remarkably plants have their maximum size all at about the same amount of temperature sums and senesce afterwards. This suggests that the growth of this species mainly depends on temperature. I assume therefore that the decreased plant sizes in the *increased* subplots are due to a too short snow free period. This finding is backed up by its wide distribution all over Svalbard and its generalist behavior (Lindner & Meister 2006) even though the species tends to prefer moist, sheltered localities like snow beds (Fahnestock et al. 2000; Lindner & Meister 2006) where it benefits from its prostrate growth form by overheating (Lindner & Meister 2006). Nevertheless, my results contrast those of Van der Wal et al. (2000) and Walsh et al. (1997, for the closely related Salix planifolia) which are contradictory by themselves inasmuch as the former study demonstrated higher leaf mass in earlier melting plots and the latter an increased growth in areas with a delayed snowmelt. From my results, I conclude that even though *S.polaris* is not negatively affected by neither an earlier nor a moderately later snowmelt, it might face a competitive disadvantage from a changing climate as compared to other species that are able to benefit from altered snowmelt regimes

In case of *Stellaria crassipes,* the *medium* treatment led to decreased plant sizes of 49%, but an even more delayed snowmelt (*increased*) showed no effect (table 14, figure 2d). The decrease in *medium* subplots suggests that the species cannot take sufficient advantage

from higher nutrient availability to compensate for the shorter growing season behind fences, whereas the results of the *increased* treatment were affected by a high loss of individuals. Because plant sizes in *removed* do not differ significantly from ambient conditions and *S.crassipes* increased its size by 64% in *shallow* subplots, I suggest that this species copes well with an exposure to spring frosts and cold winds, an early onset of leaf burst when climatic conditions are harsh and grows generally at rather dry locations like windblown ridges (Rønning et al. 1996). I conclude that the species is likely to profit from a longer growing season.

Conclusion

My study species responded idiosyncratically to the snow manipulations with little parallelism detectable neither among growth forms nor among snowbed or ridge species. But admittedly there were only eight species included in this study and the sample size per growth form or habitat preference was hence probably too low to detect significant trends.

I assume that the idiosyncratic response patterns result from the fact that plant size is not only depending on the length of the growth period, but as well on temperature sums, soil moisture and nutrient availability which interfere with the depth and duration of the snow cover. The thicker the snow pack is in an area, the more moisture, the cooler soils and the higher nutrient supply plants face after snowmelt (DeMarco et al. 2011; Jonas et al. 2008; Mallik et al. 2011; Morgner et al. 2010; Scott & Rouse 1995; Wahren et al. 2005; M. D. Walker et al. 1999; Walsh et al. 1997; Wipf & Rixen 2010). An intermediate increase of snow cover can thus lead to a beneficial trade-off for the nutrient limited high arctic vegetation (Fahnestock et al. 2000; Starr et al. 2008; Wahren et al. 2005; Walsh et al. 1997) and enhance its growth. This was the case for the species *Alopecurus magellanicus*, *Bistorta vivipara* and *Dryas octopetala* in my study. I detected an opposite effect of a moderately increased snow pack for *Pedicularis hirsuta* and *Cassiope tetragona* which were probably not able to benefit sufficiently from improved moisture and nutrient supply to compensate for the delayed snowmelt. A still later snowmelt enhanced the productivity of *B.vivipara* and *D.octopetala*, but not of *A.magellanicus*; *C. tetragona* and *Salix polaris* responded with a decrease in their average size, supposedly for the same reasons as under an intermediately increased snow pack.

Due to water influx from the surroundings into subplots where the snow was removed experimentally, the treatment *removed* does not only differ in terms of growing season

length. In fact, soil moisture, and probably nutrient availability as well, were increased instead of decreased and this treatment rather simulates a climate scenario with an increase of rain during springtime. However, an earlier snowmelt and thus a longer growing season (*shallow*) did in contrast to the common assumption for arctic ecosystems (Euskirchen et al. 2009; Stow et al. 2004) not result in an increase of photosynthetically active tissue and thus biomass for any species, neither in terms of average nor in terms of peak plant sizes. In fact, *C.tetragona*, *Luzula confusa*, *P.hirsuta* and *Stellaria crassipes* decreased both their average and peak sizes. I assume that the reason is a shift of the onset of growth and thus of the determination of leaf set towards more unsuitable climatic conditions in terms of light and warmth (Wahren et al. 2005; Marylin D. Walker et al. 1995; Wipf et al. 2009) and furthermore a more likely exposure of early and not frost hardened plant tissue to spring frosts and cold winds (Pop et al. 2000; Wipf et al. 2009; Wipf 2010). It should be noted, that this simulated earlier snowmelt might actually depart from conditions to be expected under climate change as these will also include an amelioration of early season climatic conditions that might allow species to actually benefit from earlier melting dates.

The treatment *removed* led to an enhanced growth of *D.octopetala* and *L.confusa*, which are both assumed to be ridge species (Lindner & Meister 2006; Rønning et al. 1996) and should therefore be able to cope with an early snowmelt and might have taken an additional advantage by nutrients possibly washed-in with melt water from the surroundings.

Overall, I therefore conclude from my results that there is no uniform response of high-arctic plants to climate driven changes in snow regimes and that species respond idiosyncratically across growth forms and habitat associations. I underpin, however, that experiments like the one conducted still suffer from an imperfect simulation of future conditions as (1) they do not account for the expected changes in temperature, especially during spring time and (2) neglect the interfering effects of altered moisture and nutrient supplies.

However, a corollary from my study certainly is that I cannot infer that the biomass of this ecosystem will in- or decrease by a more or less extended or shortened snow free period. Rather, I assume that whichever of the predicted changes will actually become realized in the future, local communities will respond by a shift in species composition towards those species which are better able to cope with the altered conditions in the long run. Indirectly, such a shift in species composition will probably affect community, and finally ecosystem productivity.

Acknowledgements

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Appendix

English summary

The Arctic is one of the ecosystems most affected by climate change and especially winter temperatures and precipitation sums are supposed to increase. Consequently, snow cover depth and duration, the most important drivers of growing season length in the high Arctic, will also change. Depending on the extent and temporal patterns of temperature and precipitation rise, and the associated partitioning of precipitation sums into rain and snow components, this may either entail a shortened or prolonged snow free period, respectively. These changes will likely have multiple effects on plant productivity and hence the availability of biomass for consumers. In this study, I try to assess how the growth and productivity of eight common high arctic plant species will respond to different predicted climate change scenarios by experimentally changing snowmelt dates. My results demonstrate considerable variation among species with idiosyncratic positive and negative responses of individual species to either accumulation or reduction of snow cover depth and duration. I conclude that generic predictions of effects of a changing snow pack on the productivity of arctic vegetation are hardly possible, at least if a climate change driven species turn-over in local community compositions is not accounted for.

Deutsche Zusammenfassung

Die Arktis ist eines der vom Klimawandel am meisten betroffenen Ökosysteme der Erde, wobei angenommen wird, dass sich vor allem die Wintertemperaturen und –niederschläge erhöhen werden. Folglich werden sich ebenso die Schneehöhe und ihre Persistenz ändern, welche die wichtigsten Faktoren für die Länge der Vegetationsperiode in der Arktis sind. Abhängig vom Ausmaß und dem zeitlichen Muster der Temperatur- und Niederschlagserhöhung, sowie der Aufteilung der Niederschlagsmengen in Schnee- und Regenfraktionen, kann dies entweder eine verkürzte oder verlängerte schneefreie Periode zur Folge haben. Diese Veränderungen werden vermutlich vielfache Auswirkungen auf die pflanzliche Produktivität und daher Verfügbarkeit von Biomasse für ihre Konsumenten haben. In meiner Arbeit versuche ich zu ermitteln wie das Wachstum und die Produktivität von acht typischen hocharktischen Pflanzenarten von verschiedenen vorhergesagten Klimawandelszenarien durch das experimentelle Verändern von Schneeschmelzezeitpunkten beeinflusst werden. Meine Ergebnisse zeigen erhebliche Unterschiede zwischen den Arten mit idiosynkratischen positiven und negativen Reaktionen der einzelnen Arten auf entweder eine Erhöhung oder Reduktion der Schneehöhe und ihrer Persistenz. Ich komme daher zu dem Schluss, dass allgemeine Vorhersagen von Folgen einer sich ändernden Schneedecke auf die Produktivität der arktischen Vegetation kaum möglich sind, zumindest wenn ein klimawandelbedingter Artenwechsel in lokalen Gesellschaftszusammensetzungen nicht berücksichtigt wird.

Curriculum Vitae

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University Education

02/2010 – 12/2012	Master studies in Ecology, University of Vienna (Austria)
	Key aspect: Syn- and Landscape Ecology
	Title of Master thesis: *Idiosyncratic responses of arctic plants to changing snow depths*
	Supervisors: Univ. Prof. Dr. Stefan Dullinger, University of Vienna (Austria) and Assoc. Prof. PhD Elisabeth Cooper, University of Tromsø (Norway)
08/2011 – 12/2011	Master studies in Biology, University of Tromsø (Norway)
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12/2008 – 02/2010	Bachelor studies in Biology, University of Vienna (Austria)
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08/2009 – 12/2009	Bachelor studies in Biology, University of Bergen (Norway)
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10/2006 – 12/2008	Diploma studies in Biology, University of Vienna (Austria)
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University Grants

06/2011 – 08/2011	Short-term grant abroad (KWA) for the realisation of the Master thesis on Svalbard (Norway), University of Vienna (Austria)
06/2011 – 09/2011	Julius-Payer-Grant for fieldwork on Svalbard (Norway), Österreichische Gesellschaft für Polarforschung
10/2009 – 09/2010 10/2009 – 09/2011	Performance grant for excellent academic achievements, University of Vienna (Austria)
08/2009 – 12/2009	Grant of the Erasmus Programme for one semester at the University of Bergen (Norway)

Applied scientific experience

10/2012	Participation at the *Polar Ecology Conference*, České Budějovice (Czech Republic)
04/2012 – 10/2012	Research assistant for the project *Ecosystem responses on snow depth* (University of Tromsø, Norway), Svalbard (Norway)
06/2012 – 09/2012	Research assistant for the project *Invasive species pathways* (Museum of Tromsø, Norway), Svalbard (Norway)
05/2012, 09/2012	Field assistant for Assoc. Prof. PhD Lennart Nilsen (University of Tromsø, Norway): Monitoring of high arctic tundra, Svalbard (Norway)
07/2012	Laboratory assistant for the course *Arctic terrestrial biology* at the University Centre on Svalbard (Norway)
06/2011 – 09/2011	Fieldwork for the Master thesis *Idiosyncratic responses of arctic plants to changing snow depths*, Svalbard (Norway)
06/2011 – 09/2011	Field assistant for PhD candidate Philipp Semenchuk (University of Tromsø, Norway): Investigations on phenology and reproduction of arctic plants, CO_2-flux and active layer thickness, Svalbard (Norway)
06/2011	Participation in the project meeting *Phenology in Northern Fennoscandia* (Svalbard, Norway), organised by Norut (Tromsø, Norway)
03/2011	Research assistant for the project *Bioindication of heavy metal pollution in Swiss cities* (Ecotox, Vienna, Austria)
02/2010	Fieldwork for the Bachelor thesis: Biodiversity investigations on butterflies, La Gamba (Costa Rica)
10/2009 – 01/2010	Research assistant inter alia within the project *How to prevent invasions of alien species onto urban hills and coastal heathland ecosystems: Sustaining biodiversity in cultural landscapes* (UniGlobal, Bergen, Norway)
12/2009	Participation in the international workshop *The effect of introduced trees: models & projections* (UniGlobal, Bergen, Norway)
10/2009	Field assistant for Astrid Alfredsen Msc (University of Bergen, Norway): Complementary relevés, Finse (Norway)

Further Qualifications

Language skills	German (native)
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	Spanish (basic)
	Norwegian (basic)
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