BIO 3910

MASTER'S THESIS IN BIOLOGY

The effect of vegetation type and snow depth on annual CO_2 efflux in a high arctic tundra region

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February, 2009

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Abstract

This thesis evaluates the effect of vegetation type and increased snow depth on soil temperature and annual CO_2 efflux in an arctic tundra region. Snow fences were set up to manipulate snow accumulation in heath and meadow vegetation on Spitsbergen. Field campaigns lasted from July 2007 - July 2008. CO_2 efflux, measured by means of a dark and closed-dynamic soil flux chamber, showed seasonal variation and was lowest in winter time. Soil temperature had a strong influence on efflux year-round, whereas vegetation type was a major driver in the growing season. Temperature based ecosystem respiration models were used to estimate annual efflux to 125 g C m^{-2} in heath and 162 g C m^{-2} in meadow sites. CO_2 efflux during the 241 days long winter was about 40 g C m^{-2} in both vegetation types and thus contributed significantly to the annual efflux. Snow fences enhanced snow depth with about 1 m, led to significantly higher soil temperatures and increased winter effluxes with 29-87 %. Increased snow cover resulted in a delayed start of the growing season and led to moister- and for heath sites also cooler- soil conditions in summer. In meadow sites, deeper snow cover had a negative effect on the growth of non-woody plants. The results indicate that changes in winter precipitation can affect the carbon balance of arctic tundra regions by alteration of the soil temperature regime and subsequent enhancement of winter respiration.

Keywords: CO_2 efflux, ecosystem respiration, snow depth, arctic tundra

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Preface

”Vitenskap! Er antaglig det farligste og mest fascinerende prosjekt menneskeheten har påtatt seg.”

Arne Næss

1 Introduction

The arctic, the area of the Earth which is covered by tundra vegetation north of the tree line, extends over 7.11 * 10^6 km^2 (Walker et al., 2005). This region is characterized by extreme temperature and light conditions, an extensive winter with long-lasting snow cover and a short growing season during summer. Primary productivity in arctic ecosystems is low and strongly limited by the availability of nutrients, which are provided by the recycling of soil organic matter (Shaver et al., 1992). As decomposition and mineralization processes are even more constraint than productivity, arctic ecosystems tend to accumulate organic matter, carbon (C) and other elements (Callaghan et al., 2004).

Arctic ecosystems contain at least 14 % of the stored terrestrial soil carbon (Post et al., 1982), with recent estimates being substantially higher (Ping et al., 2008), and thus significantly contribute to the global carbon budget. This soil carbon resides in different pools with different turnover times, which means that some carbon forms are rather labile and others more recalcitrant (Trumbore, 2006). Climate change is expected to affect arctic ecosystems earlier and more intensely than other terrestrial ecosystems (ACIA, 2005). Possible alteration of the net carbon balance of these ecosystems, resulting for example from changes in plant community structure and productivity (Christensen et al., 2008) or soil CO_2 release (Grogan and Chapin, 1999; Oechel et al., 1993), could modify carbon storage and in turn provide a positive feedback to climate change.

Whether the carbon balance (net ecosystem production NEP) of ecosytems is positive (C source) or negative (C sink) depends on the relationship between ecosystem respiration (C loss) and gross ecosystem production (C uptake) (Callaghan et al., 2004). The loss of C through fires, or as dissolved and particulate organic matter through hydrological discharge and as volatile organic compounds contribute to a full C budget (Trumbore, 2006). Furthermore, the carbon cycle interacts with the biogeochemical cycles of other elements such as nitrogen and phosphorus (Jacobson et al., 2000). Hence, the C balance of arctic ecosystems is the sum of different processes which vary both on temporal and spatial scales and which may respond differently to the same environmental driving factors (Christensen et al., 2008). Predicting the impact of possible changes in environmental conditions on C budgets is therefore challenging and the parts of the carbon balance that currently remains the least understood are processes controlling C loss (Christensen et al., 2008).

Photosynthesis is the single route through which CO_2 from the atmosphere enters terrestrial ecosystems. The return of this C to the atmosphere happens through a variety of biological processes which add up to the total ecosystem respiration (Trumbore, 2006). Ecosystem respiration is spatially divided into aboveground (canopy) and belowground (soil) respiration. The latter one is regarded to be the major pathway of ecosystem respiration (Illeris et al., 2004b; Schlesinger and Andrews, 2000).

Whereas aboveground respiration is mainly autotrophic, soil respiration is a combination of rhizospheric respiration (including root respiration and root associated microbes that live on root exudates) and heterotrophic respiration by microorganisms (fungi and bacteria that nourish on soil organic matter) and the soil meso- and macrofauna (Scott-Denton et al., 2006). Estimates concerning the contribution of rhizospheric respiration to total soil respiration range from 10-90 % (Chapin and Ruess, 2001). This huge variation is mainly due to the use of different methods and their uncertainties (ibid.). Annual variations in the contribution of rhizospheric respiration to total soil respiration as well as in the composition of the soil microbial communities have been observed (Björk et al., 2008; Scott-Denton et al., 2006).

The most important trace gases that are released through respiration processes are carbon dioxide (CO_2) and methane (CH_4), the latter one being produced when oxygen availability is strongly limited (Elberling et al., 2008). According to Christensen et al. (2008) the contribution of CH_4 might be as high as 10-25 % of the heterotrophic respiration when included in annual C budgets of arctic ecosystems.

A compilation of trace gas budgets for the Circumpolar North shows that arctic tundra ecosystems can act both as sources and sinks of C to the atmosphere, depending on the region studied (Christensen et al., 2008). It is important to state that interannual variability in ecosystem net CO_2 efflux is high (Christensen et al., 2008; Oechel et al., 2000). For example, a high arctic polar-semidesert site on Svalbard was in the period between snow-melt and end of summer a weak carbon sink (-3.9 ± 3.7 g C m^{-2}) in one year and a weak carbon source (5.0 ± 3.3 g C m^{-2}) in the following year (Lloyd, 2001). Grøndahl et al. (2007) assume that variations during the growing season are driven by changes in photosynthetic rate, whereas Lloyd (2001) and others have suggested that respiration is the main regulator of an ecosystems C balance both on seasonal and annual time scales and that interannual variations are due to changes in respiration rather than photosynthetic rate (Illeris et al., 2004b; Jones et al., 1998; Vourlitis and Oechel, 1999). Several studies of CO_2 efflux on Svalbard have been carried out in different vegetation types such as semipolar-desert, and wet, mesic and heath tundra, but measurements have been restricted to a few months during the growing season or are, when covering a whole year, rather limited in the non-growing season (Elberling, 2007; Lloyd, 2001; Sjögersten et al., 2006; van der Wal et al., 2007).

There are several factors that influence ecosystem respiration such as temperature, soil water content, substrate availability and quality (Davidson et al., 2006) and vegetation type, which in turn influences litter quality and thus decomposition (Grogan and Chapin, 1999). The abundance and activity of the soil micro- and macrofauna is an additional factor that affects respiration. On an annual scale, temperature is the major control for ecosystem respiration (Fang and Moncrieff, 2001; Raich and Schlesinger, 1992), but within one particular season of the year, temperature might be less important compared to the other factors mentioned above (Chimner and Welker, 2005). Respiration increases with increasing soil temperature and numerous equations have been developed to describe this temperature dependence (Davidson et al., 2006). A commonly used value to express the temperature sensitivity of respiration is the Q_{10} value, the factor by which respiration is multiplied when temperature increases by 10 ºC (Elberling et al., 2008). Temperature sensitivity varies between different soil types and temperature regimes and functional groups of soil organisms (Elberling et al., 2008) but also plant roots differ in their sensitivity to temperature increase (Cooper, 2004).

In recent years several studies have revealed that carbon loss in form of CO_2 during the nongrowing season (defined as “cold season” by Olsson et al. (2003)) in northern ecosystems is significant and must be taken into account when calculating annual carbon budgets (Brooks et al., 1995; Fahnestock et al., 1998; Fahnestock et al., 1999; Grogan et al., 2001; Oechel et al., 1997b; Sommerfeld et al., 1993; Zimov et al., 1996). The respired CO_2 in winter comes both from labile C in recently-fixed plant material as well as from C in the more recalcitrant soil organic matter pools (Nobrega and Grogan, 2007) and is mainly the result of microbial respiration (Elberling, 2007). To some extent CO_2 emissions might also be caused by plant respiration, as measurable rates of respiration have been reported for evergreen plants at 0 °C in winter (Rønning, 1969). When temperatures fall below 0 °C much of the soil water freezes, however, unfrozen water remains around soil particles down to temperatures of at least -10 °C (Romanovsky and Osterkamp, 2000) thus enabling microbial activity, which has been shown to take place at temperatures down to at least -12 °C in the field (Elberling, 2007) and to at least -39 °C in incubation experiments (Panikov et al., 2006). CO_2 loss can also occur under soil freezing during the phase change from water to ice (Coyne and Kelley, 1971) and trapped CO_2 can be released when frozen soils crack (Oechel et al., 1997b). Pulses of CO_2 release have also been measured during thawing in spring (Elberling and Brandt, 2003).

Snow depth and the timing of snow fall are main driving factors for cold season soil temperatures (Brooks and Williams, 1999; Elberling, 2007; Olsson et al., 2003) and due to the insulating effect of snow, soil temperatures can be held in a range high enough to promote the activity of soil microarthropods (Addington and Seastedt, 1999) and microbes “for some or all of the winter” (Sullivan et al., 2008, p.1). General circulation models predict that arctic regions will experience a pronounced rise in temperature as well as precipitation, especially during winter time (ACIA, 2005; Oechel et al., 1997a). An increasing amount of snow could increase the C source strength of an ecosystem in two ways; through a positive feedback on winter respiration rate and through an indirect negative effect on gross ecosystem production by shortening of the growing season (Grøndahl et al., 2007). On the other hand, increased snow depth and subsequently increased soil moisture may decrease soil CO_2 production in spring and summer as long as soil moisture content after snow-melt is above the optimum range of 12-35 vol.% (Elberling et al., 2008).

To evaluate the effect of increased winter precipitation in northern ecosystems, studies have been carried out in high-altitude ecosystems (Brooks et al., 1995; Walker et al., 1999), in moist and dry tussock tundra (Schimel et al., 2004; Wahren et al., 2005; Walker et al., 1999; Welker et al., 2000), in upland tundra (Scott and Rouse, 1995) and in birch hummock tundra (Buckeridge and Grogan, 2008; Nobrega and Grogan, 2007). It has been shown that an increase in snow depth leads to warmer soils in winter and cooler and moister soils in summer (Scott and Rouse, 1995) and that enhanced snow depth can greatly affect vegetation community (Scott and Rouse, 1995), microbial respiration and N mineralization rates (Brooks et al., 1995; Buckeridge and Grogan, 2008; Schimel et al., 2004; Wahren et al., 2005) and lead to increased winter CO_2 efflux (Brooks et al., 1995; Nobrega and Grogan, 2007; Schimel et al., 2004; Wahren et al., 2005; Welker et al., 2000).

Enhanced snow accumulation also affects the timing of snow-melt, thus controlling the onset of thawing of the active layer (Christiansen and Humlum, 2008) and constraining the length of the growing season (Shaver and Kummerow, 1992), which in turn impacts on carbon assimilation (Grøndahl et al., 2007). Rønning (1969) stated that the length of the growing season is an important factor influencing the growth of *Dryas octopetala*. *Cassiope tetragona* has shown positive growth responses to increased temperature, especially at high latitude sites (Havström et al., 1993). Short-term growth studies of *Cassiope tetragona* have found a reduction in both length and number of leaves of plants exposed to deeper snow cover in winter and lower soil temperatures in summer (Wdowiak, 2008). Others, though, did not observe any short-term effect on plant growth in Alaskan tundra sites with deeper snow and even noticed increased shrub growth despite a shortened growing season after an 8-years study period (Wahren et al., 2005; Walker et al., 1999).

2 Objectives

The aim of this study was to characterize annual CO_2 effluxes in *Cassiope* heath and *Dryas* meadow, two dominating vegetation types in an arctic tundra region, both under natural as well as experimentally increased snow depth conditions. It was hypothesized that ecosystem respiration is influenced by the extent of snow cover due to its effect on soil temperature and soil moisture. It was further hypothesized that vegetation type itself affects ecosystem respiration and therefore influences the magnitude of the response to soil temperature and moisture conditions. In detail the following predictions were made:

1) In general, CO_2 efflux will show seasonal differences and is expected to be lowest in the cold season. However, due to the long duration of winter, ecosystem respiration in this period is expected to contribute substantially to the annual CO_2 efflux.

2) Compared to ambient conditions, experimentally increased snow depth will lead to increased winter soil temperature.

3) Compared to ambient conditions, experimentally increased snow depth will lead to increased soil moisture and decreased soil temperature in the growing season.

4) Changes in soil temperature and soil moisture conditions due to experimentally increased snow depth will lead to a) increased winter CO_2 efflux and b) decreased summer CO_2 efflux.

5) There will be a difference in CO_2 efflux between the vegetation types in the growing season, when efflux is expected to be highest. CO_2 efflux will be higher in *Dryas* meadow, the vegetation type with higher substrate quality.

In addition, it was hypothesized that increased snow depth leads to prolonged snow melt in spring and hence a delayed start of the growing season. It was therefore predicted that:

6) Experimentally increased snow depth will have a negative effect on plant growth in the short-term.

Prediction 1) was investigated by measuring CO_2 efflux in the period 10th July 2007-29th July 2008 and subsequent compilation of temperature based respiration models. Predictions 2) and 3) were tested by measurements of soil temperature and soil moisture. Prediction 4) and 5) were tested by measuring CO_2 efflux. Prediction 6) was tested by measuring peak season biomass, which was harvested in the end of the experiment.

3 Material and methods

3.1 Study site description

This study was carried out on Spitsbergen, the largest island in the Svalbard archipelago. This region, situated between 74 ° N and 81 ° N, extends over 62 500 km^2 whereof 60 % is covered by glaciers (Bengtson et al., 1999). Permafrost on Svalbard is classified as continuous (Humlum et al., 2003). The landscape is dominated by mountains and large valleys shaped during previous glaciations. Due to the West Spitsbergen current, a warm branch of the North Atlantic current that extends along the West Coast of the island, climatic conditions on Spitsbergen are more favourable than in other arctic regions at the same latitude. Based on mean July temperatures the Arctic can be divided into five major bioclimatic zones (Walker et al., 2005) of which three are present on Svalbard. Following Elvebakk (1997) those are the arctic polar desert zone, the northern arctic tundra zone and the middle arctic tundra zone respectively, the latter one having the largest ecological diversity (Elvebakk, 2005). It was this zone in which fieldwork was conducted.

The study sites were situated in Adventdalen (N78°10', E16°06'), one of the largest valleys in the western part of Spitsbergen close to the main settlement Longyearbyen (Figure 1). The closest official meteorological station at Svalbard airport is located about 15 km west of the study area. According to monthly data from this station for the years 1969-1990 normal annual precipitation for the region is 190 mm, of which the major fraction is falling as snow in winter time. Normal mean annual temperature is -6.7 °C. The coldest month is February with a normal mean of -16.2 °C, the warmest month is July with a normal mean of 5.9 °C (Meteorologisk Institutt, www.eklima.no). In the period 18th April to 24th August the sun is continuously above the horizon, whereas it stays below it between 26th October and 16th February.

Bedrock in the lower parts of the valley is dominated by jurassic and cretaceous sediments, the former ones containing easily weathered calcareous shales (Hjelle, 1993). Sedimentary rocks are overlain by aeolian and fluvial deposits (Tolgensbakk et al., 2000). Hydrology is strongly influenced by the underlying permafrost. The maximum thickness of the active layer recorded at a CALM (Circumpolar Active Layer Monitoring) site, situated a few kilometres from the study site, was 105 cm in the years 2000-2007, but interannual variations can be as high as ±30 cm (Christiansen and Humlum, 2008).

The study area is, characteristically for the middle arctic tundra zone, dominated by *Cassiope tetragona* heath and *Dryas octopetala-Tomentypnum nitens* tundra (Elvebakk, 2005). Both associations belong to the same alliance, *Caricion nardinae* (Nordhagen 1935 in Rønning 1965), but differ in their ecological demands. Whilst the first one can be found on neutral to acidic substrate the latter one develops on finer textured mesic calcareous substrate (Elvebakk, 2005). *Cassiope tetragona* tundra (hence called *Cassiope* heath) can be found in more sheltered localities with a small but steady supply of moisture during the growing period (Rønning, 1965). This community is dominated by the evergreen dwarf shrub *Cassiope tetragona* which requires some snow cover in winter. In contrast *Dryas octopetala-Tomentypnum nitens* tundra (hence called *Dryas* meadow), includes the prostrate shrub *Dryas octopetala*, which is considered a chionophobous species and can be found in more exposed habitats (ibid.).

Two out of the four main study sites (Figure 1, Appendix A.1) were placed in *Cassiope* heath, with *Cassiope tetragona* dominating. Other common vascular plants in these sites are *Salix polaris*, *Saxifraga oppositifolia*, *Alopecurus borealis* and *Bistorta vivipara*. The sites are situated at the foot of mountain slopes and therefore to some extent influenced by solifluction material. The remaining two sites are situated on a river terrace in *Dryas* meadow, with evenly proportions of *Dryas octopetala* L., *Luzula arcuata ssp. confusa*, *Salix polaris* and *Bistorta vivipara*. *Dryas* meadow is, contrary to *Cassiope* heath, grazed by Svalbard reindeer *(Rangifer tarandus platyrhynchus)*, which may have a manuring effect on sites in this vegetation (Elvebakk 2005).

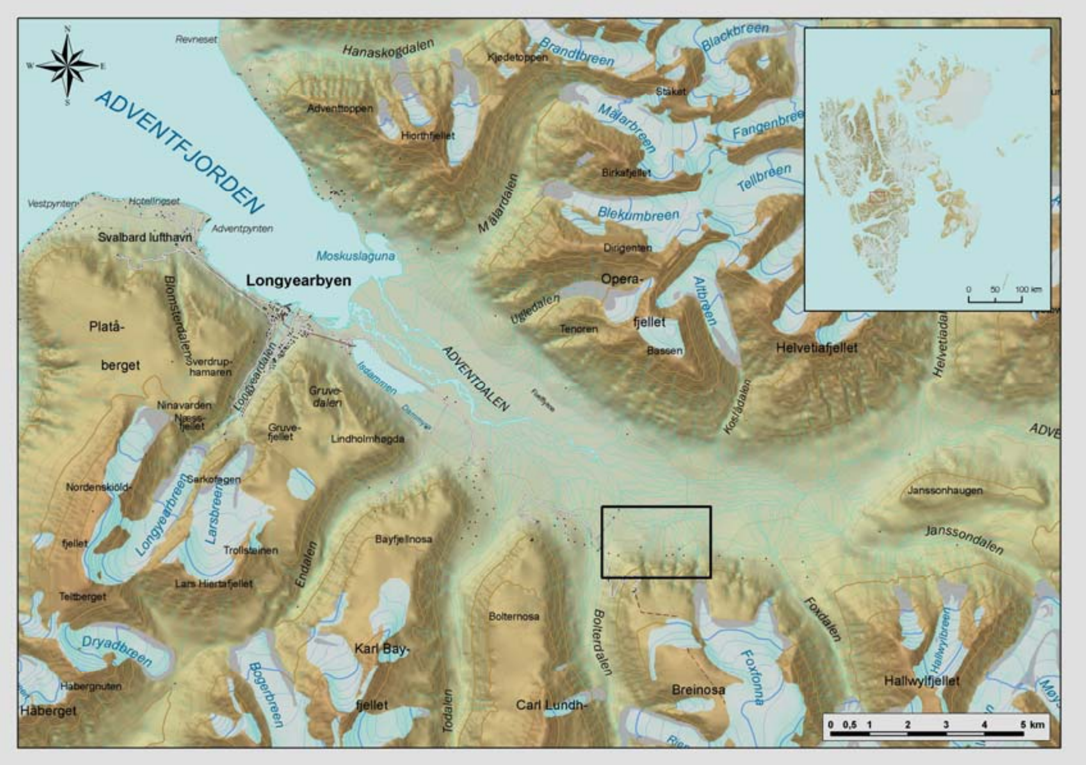

Figure 1. Map of Spitsbergen and the study region. A detailed map of the study area (black square) can be found in Appendix A.1. Source: SNSK/Norsk Polarinstitutt.

3.2 Experimental design

In each of the four different study sites (3.1) three snow fences (Figure 2) were established in autumn 2006 (Appendix A.1 Figure 15). The mean height and length of the fences is 1.5 m and 6.2 m respectively (Appendix A.1 Table 17). Fences were placed perpendicular to the prevailing wind direction, which in winter time is south-easterly, to capture the snow driven by the wind. In addition, from artificially increased snow accumulation unaffected controls were established in the same study sites, paired with each fence.

Figure 2. Snow fence in mesic *Dryas* meadow 15.8.2007, facing west (Photo: Ditte E. Strebel).

Prior to the CO_2 efflux measurements (3.4) in total 80 PVC collars (Figure 3) with a diameter and length of 10 cm * 10 cm were installed in the *Cassiope* heath sites and the *Dryas* meadow sites (Appendix A.1 Figure 15, Table 17, Table 18) 22nd and 23rd June 2007 respectively. Collars were placed in a vegetated patch to ensure that each collar enclosed either individuals of *Cassiope tetragona* (in sites A&CA, B&CB, Appendix A.1) or *Dryas octopetala* (in sites C&CC, D&CD, Appendix A.1). The height of the aboveground part of each collar was measured ten times both at time of installation and after the spring thaw and heights were used to volume-correct the CO_2 efflux measurements (Appendix C.1.1).

Figure 3. PVC collars in *Cassiope* heath (left) and *Dryas* meadow (right).

3.3 Soil properties

3.3.1 Soil temperature

Soil temperature was recorded using thermistors connected to data loggers (Tinytag, Gemini Data Loggers, West Sussex, England). Thermistors were installed at the soil surface but shielded from direct solar radiation, and at 5 cm depth with a distance of 9 m behind each fence and in each control (Appendix B.1.1). Since 5th September 2007 the data loggers registered soil temperature in hourly intervals and with a resolution of ±0.1°C. Soil temperature readings collected by Hanne H. Christiansen for the TSP Norway IPY project in the CALM sites in Adventdalen were used to model soil temperatures for the period between July 2007 and September 2007 (Appendix C.2).

3.3.2 Soil moisture and snow depth

The volumetric soil moisture content was measured with a handhold soil moisture sensor (Theta Probe ML2x, Delta-T Devices Cambridge, UK) that responds to changes in the dielectric constant of the soil, which is mainly determined by its unfrozen water content (Delta-T-Devices-Ltd, 1999). After insertion into the soil the device calculates the mean of the volumetric water content of the uppermost 7 cm. A generalised soil calibration for mineral soils was applied. In addition to calibration-dependent and instrument-specific errors, the accuracy of measurements can be negatively influenced by sampling errors due to variations in soil density and differences in insertion angle. Taking all these factors into account the accuracy of soil moisture measurements is estimated to be ±6 % (Delta-T-Devices-Ltd, 1999). Moreover the accuracy of measurements might decrease when insertion of the Theta Probe causes air pockets in or the compression of the soil (ibid.).

Five soil moisture readings were taken close to each collar (to account for heterogeneity of the soil in the study area) shortly after the CO_2 efflux measurements in order to not disturb the soil prior to those. Soil moisture could not be measured in frozen soil as it was impossible to insert the moisture probe.

Snow depth was measured manually by penetrating through the snow pack with an avalanche probe and by digging snow pits (Appendix D.1 Table 26). Due to harsh field conditions and the high time demand for digging snow pits, sampling was concentrated at sites A&CA (in *Cassiope* heath) and sites D&CD (in *Dryas* meadow, with one exception 2nd November 2007 where sites C&CC were measured instead) and the amount of replicates was reduced between January 2008 and May 2008. The distribution of snow behind each fence was measured with an avalanche probe in two rows at 2, 4, 6 and 8 m distance behind the fences, with 2 m spacing between the rows, on 20th May 2008 when field conditions had improved (Appendix B.2 Table 23).

3.4 Ecosystem CO_2 efflux

Ecosystem CO_2 efflux was measured using a LI-COR infrared gas analyzer with a portable dark and closed-dynamic soil flux chamber which includes CO_2 and water vapour analyzers in the headspace (LI-COR 6400-09/6262 Soil CO2 Flux Chamber, LI-COR, Lincoln, USA) (Figure 4). This set-up provides the most direct way to measure respiration taking place in soil and litter layers (Davidson et al., 2002). The sampled area using this flux chamber is small, which increases possible “edge effects” and thus raises the potential for measuring errors due to disturbances (Norman et al., 1997). On the other hand spatial variability of ecosystem CO_2 flux can be taken into account because the LI-COR system can be carried easily and replicate readings can cover large areas. In order to minimize disturbance of the soil and to reduce CO_2 leaking during measurements, the chamber was placed on top of permanently installed PVC collars (3.2) (Luo and Zhou, 2006).

Measurements were taken following the approach of Welles (2001) and an ambient target concentration at soil surface was determined prior to each CO_2 efflux measurement. After placing the chamber on a collar, CO_2 concentration inside the chamber was drawn down to a level of 10 ppm below target concentration with a flow rate of 700 μmol s^{-1} and under dynamic equilibrium with ambient barometric pressure. When the set concentration level was reached, the pump stopped and data was logged while CO_2 concentration in the chamber headspace was rising through the ambient concentration. The CO_2 efflux was then computed as the rate of CO_2 increase around ambient level (LI-COR, 2004). Since the extent to which CO_2 concentration prior to measurements should be decreased depends on the anticipated magnitude of efflux (Norman et al., 1997) drawdown was changed to 5 ppm below the target concentration and flow rate reduced to 500 μmol s^{-1} in the period between 2nd November 2007 and 19th June 2008, to keep the same total measuring time when effluxes were expected to be small.

To assure that measured CO_2 efflux was solely a sum of respiration processes, the start of measurements during growing season was delayed for 30 seconds after the chamber was fitted onto a collar. This time should be sufficient to ascertain cessation of photosynthesis prior to measurements (Grogan and Chapin, 2000). However, it is uncertain whether plant and root respiration is actually reduced (Elberling et al., 2004) or even increased (Körner, 2003) during short-term dark chamber measurements in the growing season and it is impossible to distinguish between autotroph and heterotroph respiration using this method (Hanson et al., 2000).

During winter time, the LI-COR system was kept in an isolated and heated container to maintain temperatures above freezing point. A similar set-up has been successfully applied in previous studies (Elberling, 2007; Elberling et al., 2004) and the detection limit of this set-up has been estimated to 0.005 µmol CO_2 m^{-2} sec^{-1}*. In order to measure ecosystem respiration rates beneath the snow rather than fluxes from the snow surface, which might be influenced by the physical properties of and possible CO_2 storage in the snow pack (Larsen et al., 2007), the snow was removed with shovels prior to the measurements. Because previous studies have reported high rates of soil CO_2 release for up to 25 minutes after the removal of snow (Grogan et al., 2001; Grogan and Jonasson, 2005) measurements were normally conducted at least 20 minutes after snow removal. However, when there were strong winds holes were quickly refilled with snow and measurements had to be made shortly after snow removal. After accomplished measurements the holes were refilled with snow. Ice lenses (4.3.4) were removed with an ice axe as far as possible without destroying enclosed plant parts in the ice.

Measurements were carried out between 10:00 h and 18:00 h and started 10th July 2007, more than two weeks after installation of the collars (3.1) in order to allow for recovering from disturbances caused by the insertion. Measurements proceeded throughout the winter, though due to harsh field conditions during that season, measurements were concentrated at site A&CA and D&CD and the amount of measurements was strongly reduced compared to summer and autumn (Appendix B.3 Table 25). Extended measurement campaigns started again 20th May 2008 in control sites and 19th June 2008 in fence sites and were carried out until 29th July 2008.

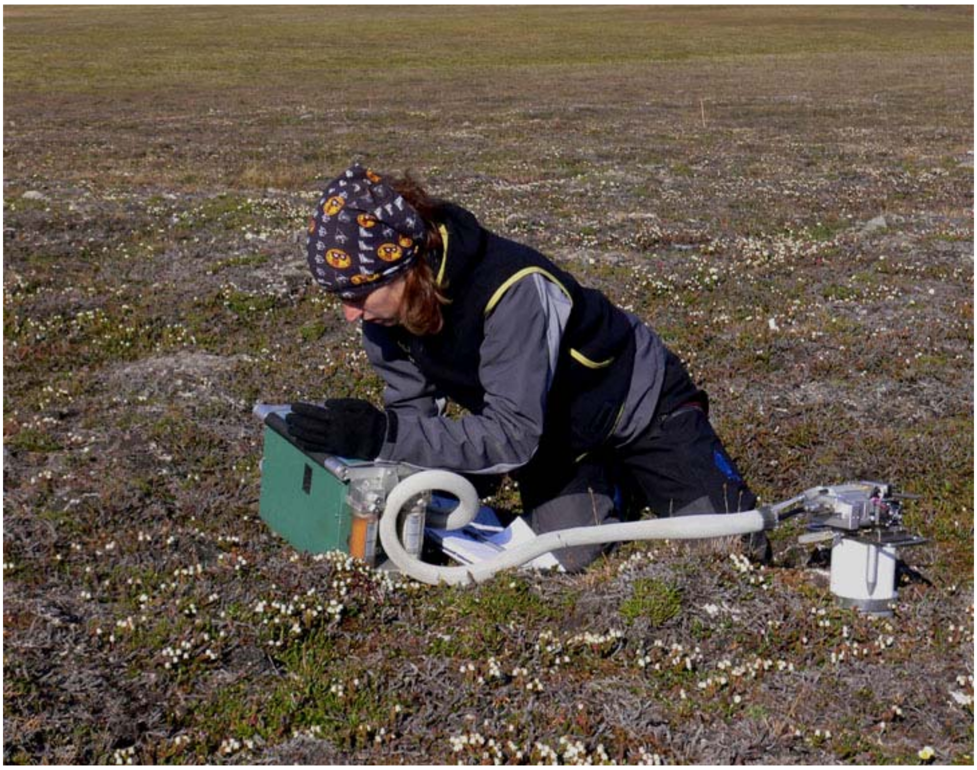

Figure 4. Measuring ecosystem CO_2 efflux in *Cassiope* heath 10.07.2007 (Photo: Elisabeth Cooper).

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* Personal communication Bo Elberling, 2008

3.5 Temperature based respiration models

In order to estimate annual CO_2 efflux, measured ecosystem respiration was related to surface soil temperature by applying a commonly used first–order exponential equation of van`t Hoff type (1) (Davidson et al., 2006; Grogan and Jonasson, 2005)

$$\text{Resp} = \alpha e^{\beta T} \text{ (where } Q_{10} = e^{\beta 10}\text{)}, \qquad (1)$$

where *Resp* is respiration rate, α and β are fitted parameters, T is measured soil temperature and Q_{10} is the temperature sensitivity of respiration. The parameters α and β where calculated specific for each treatment and vegetation type by relating mean observed effluxes to recorded soil surface temperatures for each day of measurement (Appendix C.3 Figure 18).

Ecosystems with low mean annual temperature are known to have a high interseasonal Q_{10} variability (Davidson et al., 2006) and Q_{10} values of respiration tend to decrease with increasing temperature (Fang and Moncrieff, 2001; Kirschbaum, 1995). Furthermore, abrupt increases in Q_{10} with freezing have previously been reported (Mikan et al., 2002). Taking this into consideration the model used in this study predicts daily effluxes based on separate sets of α and β for temperatures above and below 0 ºC (Appendix C.3 Figure 18). Annual efflux was then calculated as the sum of modelled daily effluxes based on recorded surface soil temperatures in the period 30th July 2007-29th July 2008.

Uncoupling of respiration and soil CO_2 release, so called "spring burst" events during soil thawing, have been reported by Elberling and Brandt (2003). Therefore, measured efflux values during spring thaw where excluded from the computation of treatment and vegetation type specific temperature sensitivities.

In addition, measurements in control sites at soil temperatures below -18 ºC recorded in end of March 2008 (Appendix B.3 Table 25) were excluded to increase the fit of the model.

3.6 Biomass

The ways in which assimilated carbon is processed in plants are complex and there is a mismatch between photosynthetic rate and biomass production (Körner, 2006). Therefore, in order to evaluate effects of increased snow cover on plant growth, peak season biomass was quantified. The vegetation and soil from all 56 installed collars at sites A&CA and D&CD (Appendix A.1) was harvested 29th July 2008 in order to estimate productivity during growing season and to evaluate a possible treatment effect in the different vegetation types. Turves inside the collars were extracted to a depth of 10 cm and divided into above- and belowground biomass in the field. Directly after returning from the field to the laboratory aboveground biomass (both alive and dead plant material) was sorted into “Cassiope” (alive and dead plant material of *Cassiope tetragona*), “Dryas” (alive and dead plant material of *Dryas octopetala*) and “Rest”, which included alive and dead plant material of all other vascular plants and the moss layer; and then immediately dried in 70 °C for seven days. Belowground biomass samples were stored in a dark fridge at 4 °C for two days before roots were washed out and dried at 70 °C for five days. After drying, both aboveground and belowground samples were stored in room temperature for 19 days before they were dried once again for two hours in 70 °C and then put into a desiccator prior to the weighing procedure. Due to loss of samples during handling only 9 and 11 out of 14 samples could be analyzed from sites D&CD respectively.

3.7 Meteorological data

In addition to the official weather station at Svalbard airport, which provided the precipitation data used in this study, there is a weather station run by UNIS in Adventdalen, 6 km west of the study area. Since the UNIS weather station is closer to the snow fence site than the airport, air temperature at 4 m and wind direction data from this station was used. Precipitation is not recorded in this station.

3.8 Data processing and statistical analysis

In order to account for the seasonal character of the data I divided the complete data set (except for data on biomass) into four different time periods, the main seasons summer, autumn, winter and spring, and tested each time period separately following Crawley (2005). In addition, soil moisture and CO_2 efflux readings from each collar were averaged and statistical analysis was then carried out on the means to avoid pseudoreplication (Crawley, 2005).

The different seasons were divided according to the following definitions. End of spring was defined as the first day when all sites were snowfree. End of summer was defined as the first day when soil surface temperatures in any of the sites dropped and stayed below 5 ºC (which happened first in *Dryas* meadow control sites). End of autumn was defined as the first day with snow cover in all sites. The first day when soil surface temperature increased above 0 ºC marked the end of winter (which happened first in *Dryas* meadow control sites). In this way it was assured that both control and fence sites would actually experience “real” summer and winter conditions in the defined summer and winter seasons. This manner of defining the seasons implied a reduction in the length of winter for sites where thawing started later and a reduction in the length of summer for sites that melted out earlier.

Because of the occurrence of an extreme winter warming event around New Year 2007/2008 (4.3.4) the winter season was divided into early winter (winter days before 1st January 2008) and late winter (winter days from 1st January onwards).

Evaluations of significant ($p < 0.05$) variations between vegetation types and treatments were performed in R 2.7.1. Data was tested for normal distribution using Shapiro-Wilk Tests. A detailed description of the statistics applied can be found in the following section.

3.8.1 Detailed description of statistical analysis

3.8.1.1 Soil moisture

Expecting a strong influence of snow-melt on soil moisture content I decided to modify the division into the four main seasons (3.8) for soil moisture analysis in the period around snow-melt and included measurements until 2nd July 2008 into the spring season, in order to be able to evaluate treatment specific effects on soil moisture even late in the main growing season.

Measurements in early June were not included in statistical analysis due to the low numbers of replicates when soils were still partly frozen (Appendix D.3 Table 28). T-tests were applied to evaluate significant differences between the two vegetation types and treatments.

3.8.1.2 Soil temperatures

Soil temperatures in summer 2007 were modelled (3.3.1) based on data from summer 2008, so no statistical tests were performed for this particular time period. Recording of soil temperatures started 5th September 2007 and statistical analysis for the autumn season starts with this day. One-way ANOVAs and Wilcoxon test were performed on normal distributed and non-normal distributed data respectively.

3.8.1.3 Snow depth

Analysis of snow depth data included evaluation of *a)* differences between the vegetation types and treatments in early winter, *b)* differences between the treatments at time of maximum snow depth and *c)* snow distribution patterns behind each fence at time of maximum snow depth.

a) Snow depth was assessed on different days in the two vegetation types and measurements were therefore grouped into different time periods. Vegetation type specific differences in control sites were tested separately for each period. The tested periods were mid October (10.10.2007 and 18.10.2007), late October (25.10.2007 and 2.11.2007), mid November (15.11.2007 and 19.11.2007) and late November (28.11.2007 and 6.12.2007) (see Table 7 for which sites were measured at the according dates). Normal distributed data were then analysed using One-way ANOVA, whereas non-normal distributed data were analysed with a non-parametric Wilcoxon test.

Treatment-specific differences in snow depth in the different vegetation types in early winter (18.10.2007 for *Dryas* meadow, 25.10.2007 for *Cassiope* heath) were evaluated by One-way ANOVA applied on data from each vegetation type separately.

b) Differences between the treatments at time of maximum snow depth were performed for each vegetation type separately. One-way ANOVA was applied on normal distributed data whereas non-normally distributed data were tested with a non-parametric Wilcoxon test.

c) Snow distribution was analysed with One-way ANOVA for each fence separately.

3.8.1.4 CO_2 efflux

T-tests and Wilcoxon tests were performed to evaluate differences in CO_2 efflux between the treatments and vegetation types. A restricted number of replicates in late winter were taken (Appendix B.3 Table 25), so statistical analysis was carried out solely on data from early winter. In order to evaluate these data for any significant treatment effect, the last days of measurement when the effect of differences in snow depth was expected to be most pronounced, were analysed. CO_2 efflux values obtained during spring-burst (3.5) were excluded from statistical analysis.

3.8.1.5 Biomass

Data from control sites were evaluated for differences between the vegetation types. Differences between the treatments were analysed for each vegetation type separately and One-way ANOVAs were applied on normal distributed data, whereas Wilcoxon tests were applied on data that were non-normally distributed.

4 Results

Daily mean air temperature and precipitation during the entire study period (10th July 2007-29th July 2008) are shown in Figure 5. Mean air temperature in this period was -4.0 °C. The warmest month was July 2007 with a mean air temperature of 6.7 °C. The coldest month was March 2008 with a mean air temperature of -17.1 °C.

Except for the period December until February, mean monthly air temperature was below the normal mean monthly air temperature for the years 1997-2007.

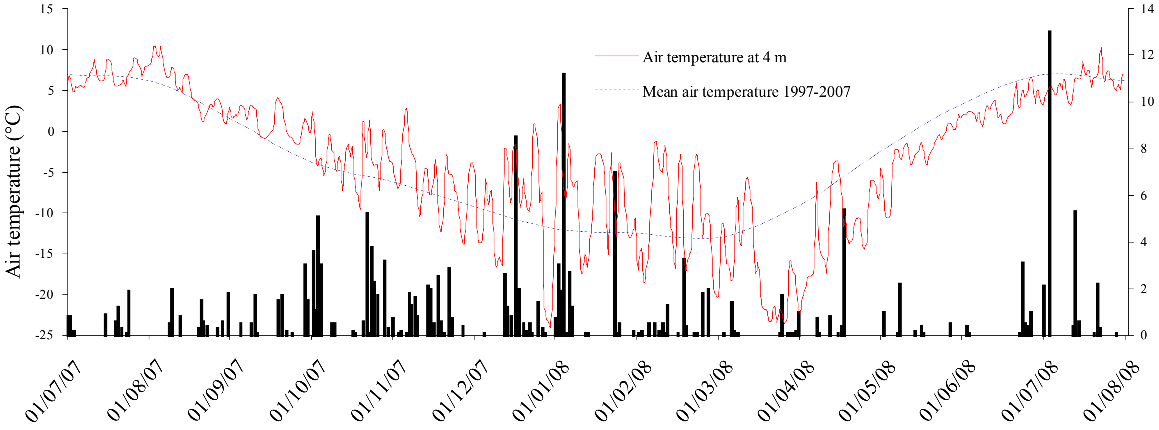

Figure 5. Daily mean air temperature (red line) and precipitation (black bars) during the study period 2007-2008. Mean monthly air temperature for the years 1997-2007 is shown with a blue dashed line. Air temperature at 4 m from UNIS weather station in Adventdalen. Mean monthly temperature and precipitation from Svalbard airport (www.eklima.no).

A total of 181 mm of precipitation was recorded for the entire study period. Monthly precipitation was below the mean monthly precipitation for the previous 10 years, except for October and December (Figure 6). The months July 2007 until September 2007 were exceptionally dry compared to the 10 years normal (Figure 6).

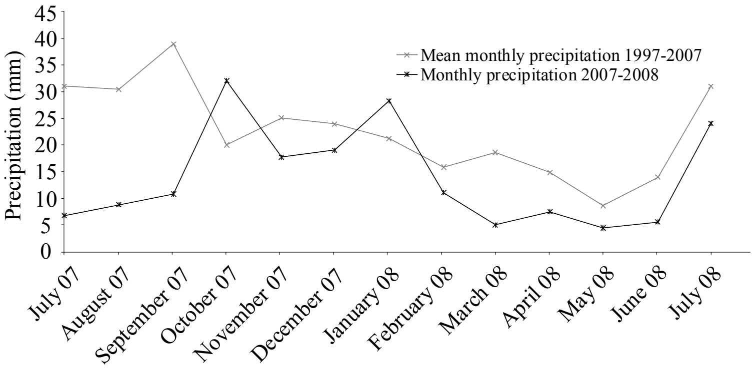

Figure 6. Monthly precipitation in the period July 2007-July 2008 and mean monthly precipitation for the years 1997-2007. Data from Svalbard airport (www.eklima.no).

The whole data set was divided into four different seasons (3.8) based on measured soil surface temperatures (Table 1) and date of complete snow-melt (Table 7):

1. *Summer*: including the days between 23rd June -17th August
2. *Autumn*: including days between 18th August-1st October
3. *Winter*: including days between 2nd October-29th May
4. *Spring*: including days between 30th May-22nd June

These seasons will be presented separately in the following section.

Table 1 Dates when mean daily surface soil temperatures in the two different treatments in *Cassiope* heath and *Dryas* meadow fell below and rose above 0 ºC and 5 ºC during the entire study period from 10.7.2007-29.7.2008. Dates in brackets indicate dates from which on soil temperatures remained above or below those temperatures for at least 7 days. Soil temperatures during winter warming event (4.3.4) are not included.

Soil temperature at surface	*Cassiope* heath Control Date	*Cassiope* heath Fence Date	*Dryas* meadow Control Date	*Dryas* meadow Fence Date
<5 °C	18.8.(18.8.)	17.8.(17.8.)	17.8.(17.8.)	17.8.(17.8.)
<0 °C	11.9.(8.10.)	11.9.(21.9.)	12.9.(2.10.)	12.9.(2.10.)
>0 °C	31.5.(31.5.)	13.6.(13.6.)	30.5.(30.5.)	1.6.(1.6.)
>5 °C	10.6.(2.7.)	26.6.(2.7.)	9.6.(2.7.)	24.6.(2.7.)

4.1 Summer

This study covered two field summer seasons, the period 10th July 2007-17th August 2007 and the period 23rd June 2008-29th July 2008.

Total precipitation during the days 10th July 2007-17th August 2007 was 8.3 mm compared to 29.1 mm in the period 23rd June 2008-29th July 2008 (Figure 5). Mean air temperature in field summer season 2007 was 7.2 ºC and 5.7 ºC the following year (Figure 5).

4.1.1 Soil temperature and moisture

4.1.1.1 Soil moisture

Volumetric soil moisture during summer was measured in the period 10th-11th July 2007 and 10th-29th July 2008. Soil moisture content during summer 2007 was significantly lower in *Cassiope* heath control (t = -3.174, df = 34.452, p-value = 0.003, T-test) and fence (t = -6.229, df = 37.969, p-value < 0.001) sites (Figure 7) compared to the same treatments in *Dryas* meadow (Figure 8, Figure 9, Figure 10). Mean soil moisture during this period was 33 vol. % in *Dryas* meadow controls compared to 26.6 vol. % in *Cassiope* heath control sites (Table 2). The comparative values for fence treatments were 43.3 vol. % in the meadow and 28.3 vol. % in the heath. In summer 2008 soil moisture content between the two vegetation types did not differ significantly, neither between controls nor between fence sites (Figure 9, Figure 10).

Table 2 Mean volumetric soil moisture content (vol. %) for the two treatments controls and fences in *Cassiope* heath and *Dryas* meadow during different time intervals of the study period. For exact days of measurements and numbers of replicates see Appendix D.3 Table 28.

	Cassiope heath		*Dryas* meadow	
	Control (vol %)	Fence (vol %)	Control (vol %)	Fence (vol %)
10.7.-11.7.2007	26.6	28.3	33	43.3
22.8.-19.9.2007	26.7	27.4	27.9	29.0
3.10.2007	6.1	7.5	6.8	7.9
19.6.-2.7.2008	37.6	52.5	45.0	60.8
10.7.-29.7.2008	29.0	34.0	29.4	33.2

Soil moisture content in control sites in the same vegetation type did not differ significantly between the two subsequent years, whereas soil moisture in sites with artificially increased snow accumulation differed significantly both in *Cassiope* heath (Figure 7) and in *Dryas* meadow (Table 2, Figure 8). Whilst soil moisture content in *Cassiope* heath fence sites was significantly higher (t = -2.695, df = 35.157, p-value = 0.011) in summer 2008 (34 vol. %) compared to 2007 (28.3 vol. %) it was significantly lower (t = 4.615, df = 36.059, p-value < 0.001, T-test) for the same period in *Dryas* meadow fence sites (33.2 vol. % compared to 43.3 vol. %) (Table 2).

Sites with increased snow accumulation in *Cassiope* heath did not show a significant higher soil moisture content than control sites in summer 2007. The difference in soil moisture between the treatments was significant (t = -3.177, df = 33.018, p-value = 0.003, T-test) in the following year (Table 2, Figure 7). In *Dryas* meadow, significantly higher soil moisture content during summer could be observed in fence sites both in the year 2007 (t = -4.348, df = 37.887, p-value < 0.001, T-test) and 2008 (t = -2.286, df = 32.786, p-value = 0.029, T-test) (Table 2, Figure 8).

4.1.1.2 Soil temperature

Mean daily soil temperature both at surface and in 5 cm depth was higher in the period 10th July-17th August 2007 (Table 3) than between 23rd June-29th July 2008 (Table 4) in all treatments and vegetation types.

Table 3 Mean soil temperatures (ºC) both at surface and in 5 cm depth in the different treatments and vegetation types in the period 10.7.2007-17.8.2007. Data is modelled based on recorded soil temperatures at the CALM site in Adventdalen (3.3.1).

	Cassiope heath		*Dryas* meadow	
	Control (ºC)	Fence (ºC)	Control (ºC)	Fence (ºC)
surface	9.2	8.1	8.4	8.8
5 cm depth	6.4	4.7	5.7	5.9

Table 4 Means of hourly recorded soil temperatures (ºC) both at surface and in 5 cm depth in the different treatments and vegetation types in the period 23.6.2008-29.7.2008.

	Cassiope heath		*Dryas* meadow	
	Control (ºC)	Fence (ºC)	Control (ºC)	Fence (ºC)
surface	7.9	6.7	7.1	7.3
5 cm depth	5.0	3.2	4.3	4.0

In summer 2008 surface soil temperature was significantly higher in control sites compared to fence sites in *Cassiope* heath (F=20.752, P < 0.001, ANOVA) whereas in *Dryas* meadow no significant difference between the treatments could be observed (Table 4, Figure 7, Figure 8).

Surface soil temperature differed between the vegetation types; daily mean surface soil temperatures in *Cassiope* heath were significantly higher in control sites (F=13.835, P<0.001, ANOVA) but significantly lower in fence sites (F=4.976, P=0.027, ANOVA) compared to the same treatments in *Dryas* meadow (Figure 9, Figure 10). Analogous patterns could be observed in soil temperatures at 5 cm depth (Table 4).

Surface soil temperatures showed diurnal variations that differed between the vegetation types. Whereas in control sites the daily minimum was recorded in *Dryas* meadow for all 37 days in summer 2008, for 20 of these 37 days daily maximum values were recorded in *Cassiope* heath (Appendix B.1.2 Table 21). In fence sites daily minimum temperatures during this period were recorded for 30 days in *Cassiope* heath, whereas for 33 days in summer 2008 the daily maximum soil temperatures were recorded in *Dryas* meadow (Appendix B.1.2 Table 21).

4.1.2 CO_2 efflux

Highest mean effluxes in all treatments and vegetation types for the entire study period were measured during the two field days in summer 2007 (Figure 7, Figure 8). Mean efflux in controls and fences in *Cassiope* heath in summer 2007 was 1.34 g CO_2-C m^{-2} d^{-1} (hence written as g C m^{-2} d^{-1}) and 1.38 g C m^{-2} d^{-1} compared to 0.67 g C m^{-2} d^{-1} and 0.84 g C m^{-2} d^{-1} in summer 2008. In *Dryas* meadow mean measured CO_2 efflux was 2.29 g C m^{-2} d^{-1} and 1.89 g C m^{-2} d^{-1} for control and fence sites in summer 2007 and 1.36 g C m^{-2} d^{-1} and 1.21 g C m^{-2} d^{-1} for the same treatments in summer 2008 (Table 5).

Table 5 Mean measured ecosystem CO_2 efflux (g C m^{-2} d^{-1}) for the different time periods of this study. For dates when measurements were conducted and values of daily effluxes see Appendix B.3 Table 24.

	Cassiope heath		*Dryas* meadow	
	Control	Fence	Control	Fence
Season	Mean ecosystem CO_2 efflux (g C m^{-2} d^{-1})			
Summer 2007	1.34	1.38	2.29	1.89
Autumn	0.65	0.68	0.77	0.83
Early winter	0.27	0.33	0.35	0.42
Late winter	0.2	0.32	0.11	0.17
Spring	0.71	0.7	0.89	0.85
Summer 2008	0.67	0.84	1.36	1.21

CO_2 efflux in control and fence sites in *Cassiope* heath was significantly lower than in the equivalent treatments in *Dryas* meadow both in summer 2007 (difference between the controls: $t = -5.382$, $df = 36.154$, p-value < 0.001, T-test; difference between the fences: $W = 100$, p-value $= 0.006$, Wilcoxon test) and in summer 2008 (difference between the controls: $W = 67$, p-value < 0.001, Wilcoxon test; difference between the fences: $W = 99$, p-value $= 0.01$, Wilcoxon test) (Figure 9, Figure 10). No significant difference in efflux between the treatments in the specific vegetation types could be observed in the summers 2007 and 2008.

Correlation of measured effluxes with soil moisture and soil surface temperature respectively, was used as a mean to visualize the possible driving effect of these two factors, even though they are intimately connected with each other. This is clear to see in spring 2008 when the temporal trends of soil moisture and soil temperature are of opposite sign (Figure 7, Figure 8). Correlations of effluxes with these two factors were therefore calculated for the period 10th July-29th July 2008 when soil moisture began to stabilize after the spring melt. Whereas CO_2 efflux in the different treatments and vegetation types was positively correlated with surface soil temperature (correlation coefficients of 0.61 and 0.76 for controls and fences in *Cassiope* heath and 0.99 and 0.71 for controls and fences in *Dryas* meadow respectively) it was negatively correlated with soil moisture (correlation coefficients of 0.79 and 0.84 for controls and fences in *Cassiope* heath and 0.12 and 0.46 for controls and fences in *Dryas* meadow respectively) (Figure 11).

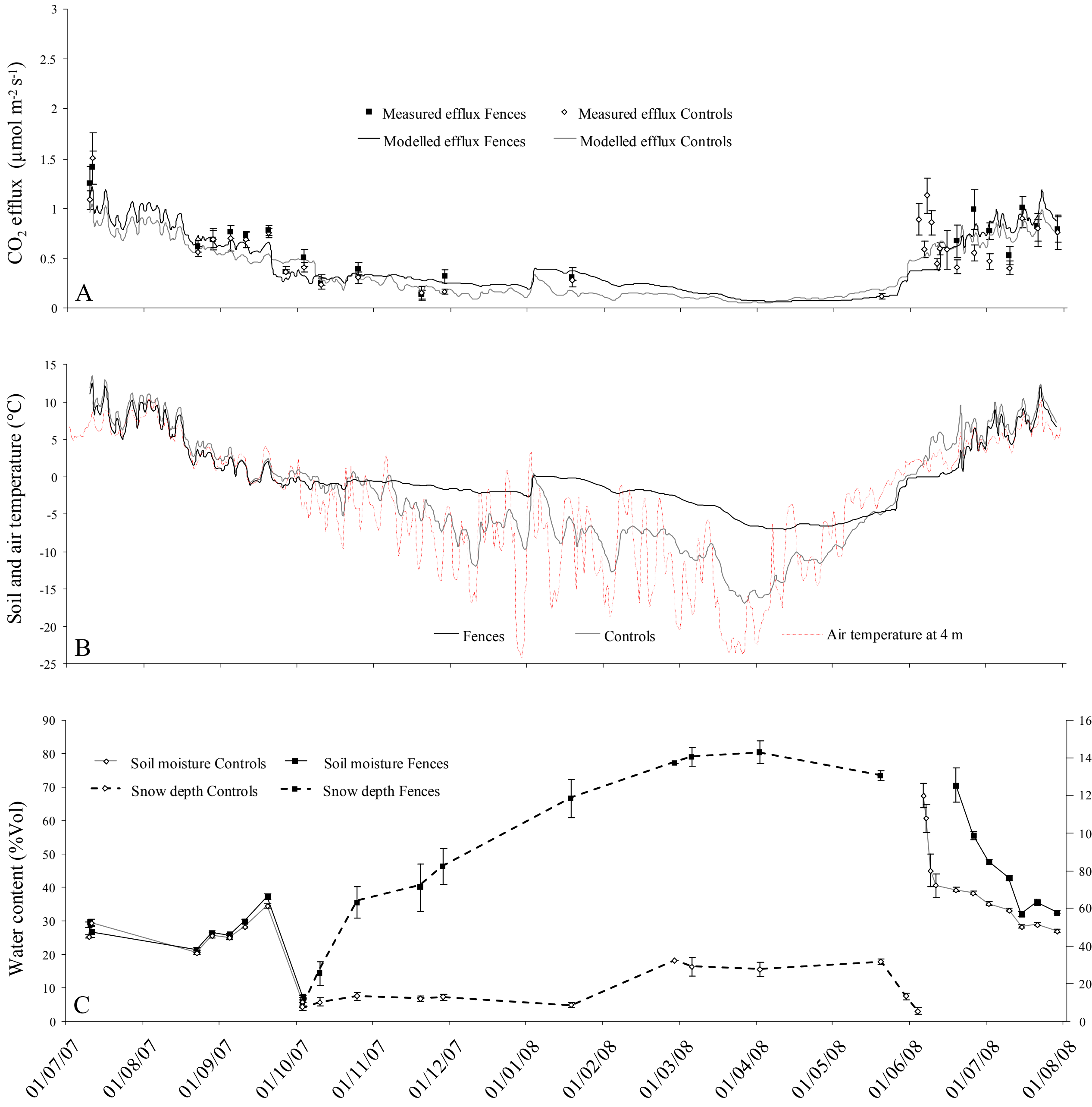

Figure 7. Comparison of temporal trends in control and fence sites in *Cassiope* heath. Open diamonds and grey lines are data from control sites. Filled squares and black lines are data from fence sites: A) mean measured CO$_2$ efflux as well as modelled CO$_2$ efflux; B) soil surface temperature and air temperature (red, dotted line) and C) soil water content (bold lines) as well as snow depth (dashed lines). Bars present standard errors of the means. For numbers of replicates see appendices B.1.1, B.3, D.1 and D.3.

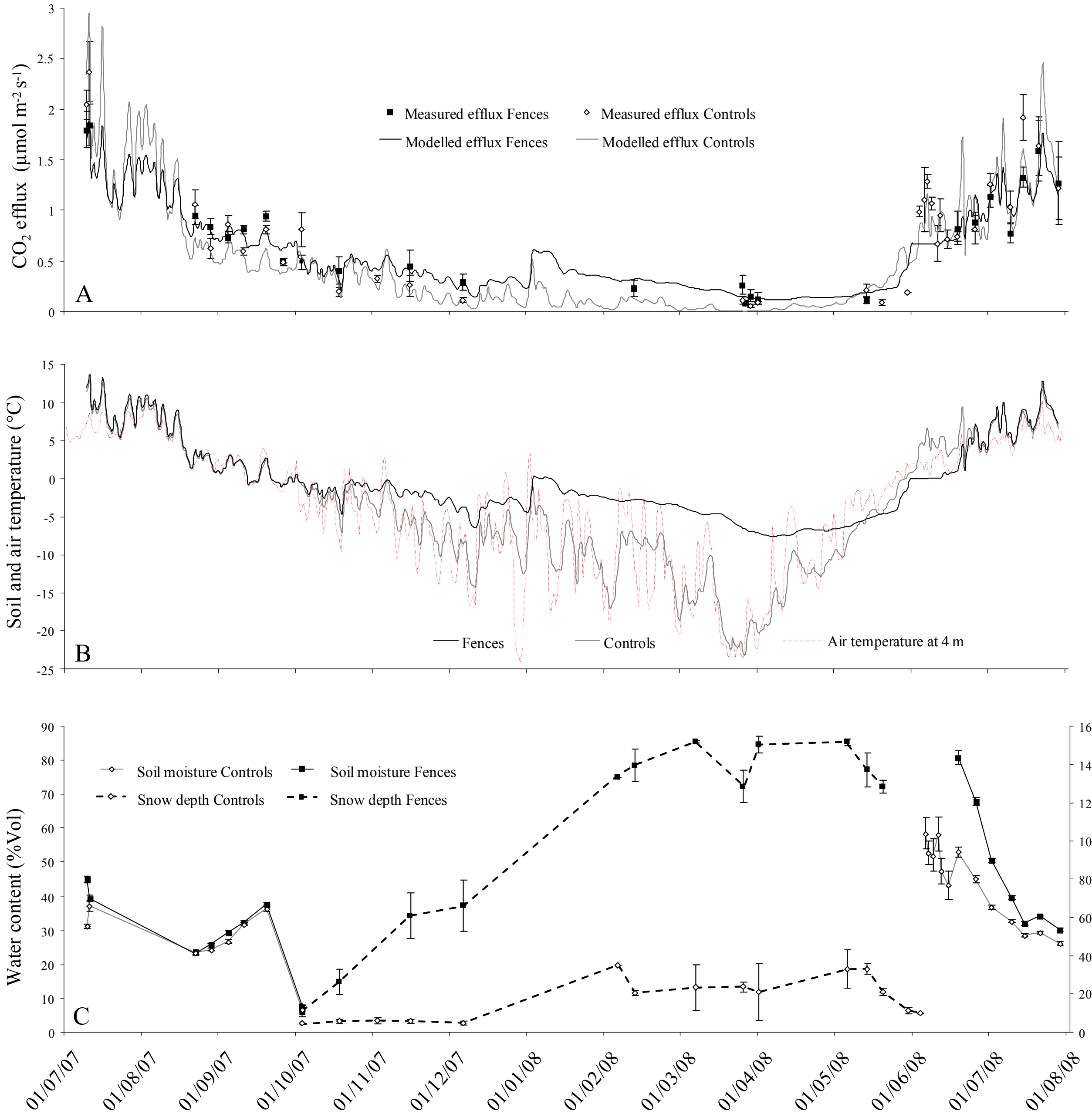

Figure 8. Comparison of temporal trends in control and fence sites in *Dryas* meadow. Open diamonds and grey lines are data from control sites. Filled squares and black lines are data from fence sites: A) mean measured CO$_2$ efflux as well as modelled CO$_2$ efflux; B) soil surface temperature and air temperature (red, dotted line) and C) soil water content (bold lines) as well as snow depth (dashed lines). Bars present standard errors of the means. For numbers of replicates see appendices B.1.1, B.3, D.1 and D.3.

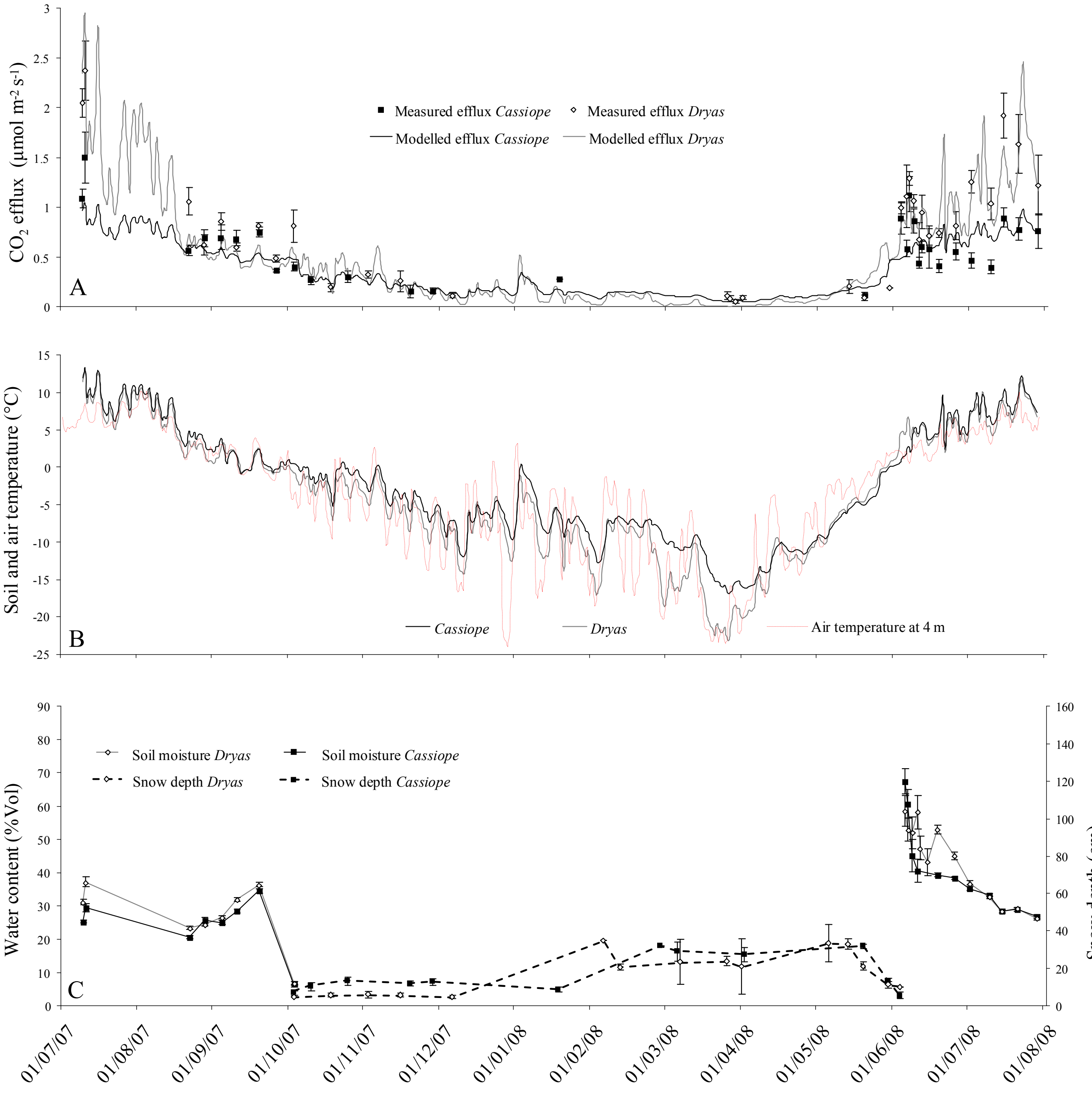

Figure 9. Comparison of temporal trends in control sites in *Cassiope* heath and *Dryas* meadow. Open diamonds and grey lines are data from *Dryas* meadow. Filled squares and black lines are data from *Cassiope* heath: A) mean measured CO_2 efflux as well as modelled CO_2 efflux; B) soil surface temperature and air temperature (red, dotted line) and C) soil water content (bold lines) as well as snow depth (dashed lines). Bars present standard errors of the means. For numbers of replicates see appendices B.1.1, B.3, D.1 and D.3.

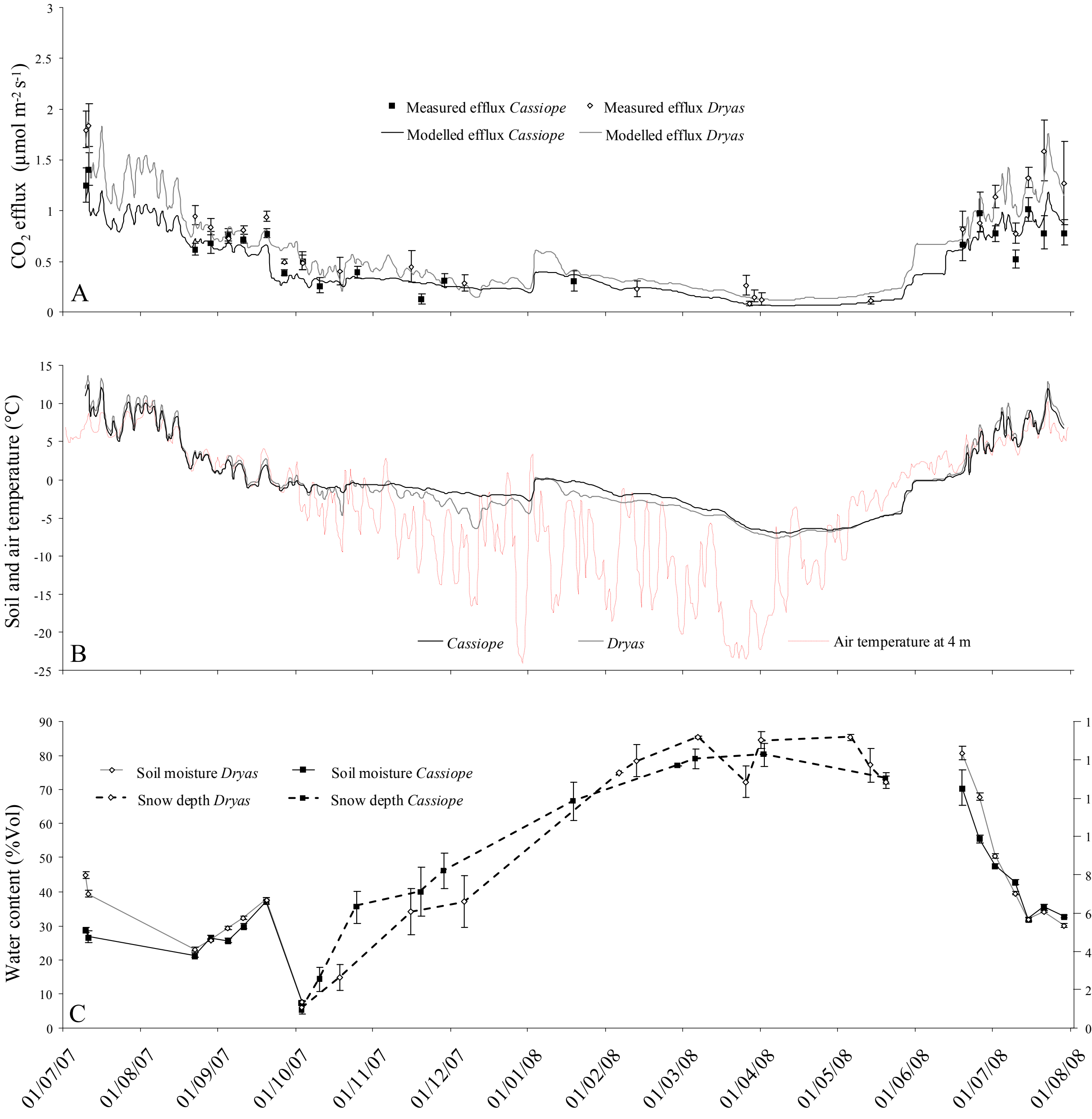

Figure 10. Comparison of temporal trends in fence sites in *Cassiope* heath and *Dryas* meadow. Open diamonds and grey lines are data from *Dryas* meadow. Filled squares and black lines are data from *Cassiope* heath: A) mean measured CO$_2$ efflux as well as modelled CO$_2$ efflux; B) soil surface temperature and air temperature (red, dotted line) and C) soil water content (bold lines) as well as snow depth (dashed lines). Bars present standard errors of the means. For numbers of replicates see appendices B.1.1, B.3, D.1 and D.3.

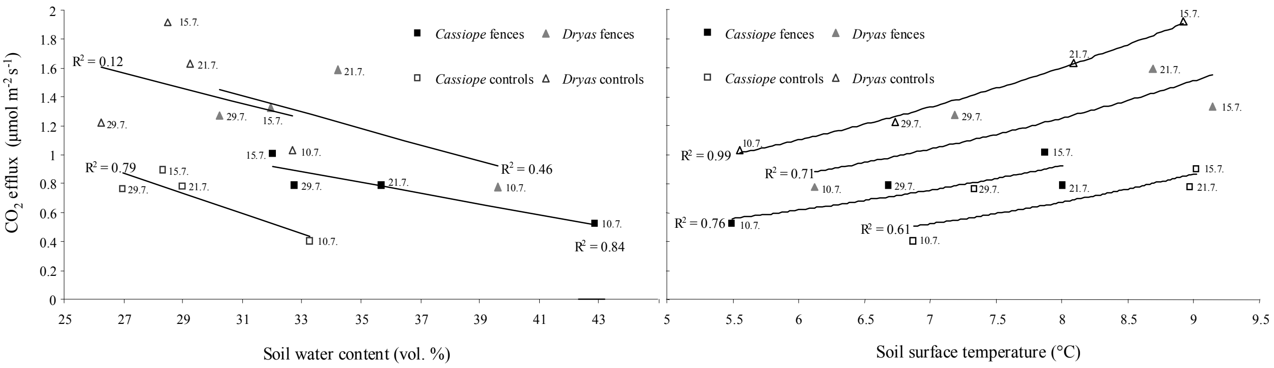

Figure 11. Mean measured CO_2 efflux versus mean measured soil moisture (left) and mean surface soil temperature (right) in control and fence sites in *Cassiope* heath and *Dryas* meadow in the period 10.7.-29.7.2008. Linear regression fits for the correlation of effluxes and soil water content as well as exponentiall regression fits for the correlation of effluxes and temperatures are shown as lines. Corresponding R^2 values are shown. Dates of measurement are added to each data point. Numbers of replicates are shown in Appendix B.3 Table 25 and Appendix D.3 Table 28.

4.2 Autumn

Autumn season was the period between 18th August 2007 and 1st October 2007. Mean air temperature during this time was 1.5 °C and total precipitation was 19.9 mm (Figure 5).

4.2.1 Soil temperature and moisture

4.2.1.1 Soil moisture

Soil moisture content in autumn did not differ significantly, neither between the treatments nor between the vegetation types. Mean soil moisture content in the period 22nd August-19th September 2007 was 26.7 vol. % and 27.4 vol. % in controls and fences in *Cassiope* heath and 27.9 vol. % and 29 vol. % in *Dryas* meadow respectively (Table 2). Soil moisture content in autumn increased with time in all treatments and vegetation types (Figure 7, Figure 8).

4.2.1.2 Soil temperature

Mean soil surface temperatures for the different treatments and vegetation types in the period 18th August-1st October 2007 were 1.8 °C and 0.9 °C in control and fence sites in *Cassiope* heath and 1.2 °C and 1.3 °C in the control and fence sites in *Dryas* meadow respectively (Table 6). The difference between the mean temperature at soil surface and at 5 cm depth was less than 1 °C (Table 6).

In the period 5th September-1st October 2007 no significant difference between controls in *Dryas* meadow and *Cassiope* heath could be observed (Figure 9). Mean daily soil surface temperature in this period was significantly higher in fence sites in *Dryas* meadow compared to fence sites in *Cassiope* heath (W = 4014, p-value = 0.001, Wilcoxon test) (Figure 10). Soil surface temperature was significantly higher in controls in *Cassiope* heath compared to fence site in this vegetation type (W = 6928.5, p-value = 0.001, Wilcoxon test) (Figure 7). There was no significant difference in soil surface temperature between the treatments in *Dryas* meadow (Figure 8).

Table 6 Mean soil temperatures (ºC)both at surface and in 5 cm depth in the different treatments and vegetation types in the period 18.8.2007-1.10.2007. Data before 5.9.2007 is modelled based on recorded soil temperatures at the CALM site in Adventdalen (3.3.1). Data from 5.9.2007 are means of hourly recorded soil temperatures.

	Cassiope heath		*Dryas* meadow	
	Control (ºC)	Fence (ºC)	Control (ºC)	Fence (ºC)
surface	1.8	0.9	1.2	1.3
5 cm depth	1.2	0.6	0.9	0.8

In autumn surface soil temperatures started to fall below 0 ºC (Table 1). On 5th September 2007, when soil temperature measurements with data loggers started, hourly recorded surface soil temperatures in both treatments and vegetation types began to drop below 0 ºC (Appendix B.1.2 Figure 16). About one week later mean daily surface soil temperatures also decreased below 0 ºC (Table 1). Mean daily surface soil temperatures fluctuated between above and below 0 ºC for 10 and 20 days in fence sites and for 27 and 20 days in control sites in *Cassiope* heath and *Dryas* meadow respectively (Figure 7, Figure 8).

4.2.2 CO_2 efflux

Ecosystem CO_2 efflux decreased in autumn 2007 compared to summer 2007 (Figure 7, Figure 8). Mean measured CO_2 efflux this period was 0.65 g C m^{-2} d^{-1} and 0.68 g C m^{-2} d^{-1} in control and fence sites in *Cassiope* heath. Corresponding efflux values in *Dryas* meadow were 0.77 g C m^{-2} d^{-1} and 0.83 g C m^{-2} d^{-1} (Table 5).

CO_2 efflux in fence sites in *Cassiope* heath was significantly lower than in fence sites in *Dryas* meadow ($t = -2.675$, df = 34.131, p-value = 0.011) (Figure 10). In control sites no significant difference in CO_2 efflux between the two vegetation types could be observed (Figure 9).

There was no significant difference in efflux between control and fence sites neither in *Dryas* meadow nor in *Cassiope* heath (Figure 7, Figure 8).

4.3 Winter

Winter season lasted from 2nd October 2007 until 29th May 2008. Because of a winter warming event (4.3.4) this time period was divided into early winter (2.10.2007-31.12.2007) and late winter (1.1.2008-29.5.2008). In early winter mean air temperature was -6.7 ºC and total precipitation was 65.1 mm. In late winter mean air temperature was -10.2 ºC and total precipitation was 56.4 mm (Figure 5). The prevailing wind direction in the period 2nd of October 2007-30th of May 2008 was south-east (Figure 12).

4.3.1 Soil moisture

In the beginning of October 2007, when soil freezing had already begun, mean volumetric soil moisture content dropped to 6.1 vol. % and 7.5 vol. % and 6.8 vol. % and 7.9 vol. % in controls and fences in *Cassiope* heath and *Dryas* meadow respectively (Table 2, Figure 7, Figure 8).

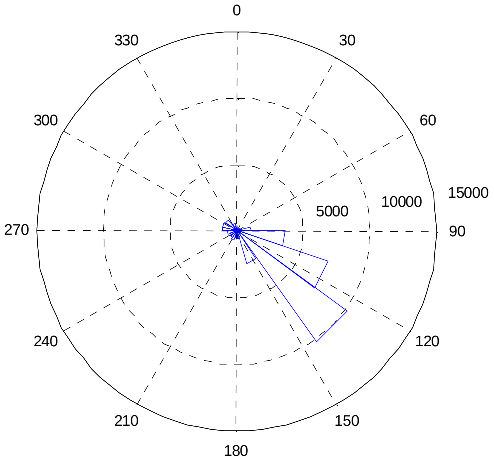

Figure 12. Windrose showing recorded wind direction in the period 2.10.2007-30.5.2008 for the study area. Numbers between 0 and 330 indicate degrees from north. Numbers others than degrees indicate numbers of observations in the specific degree intervals marked with blue. Wind direction was recorded every ten minutes. Data from meteorological station in Adventdalen plotted in MATLAB 7.0.1.

4.3.2 Snow depth

The first snow was observed in the study area in beginning of October 2007 (Figure 7, Figure 8). A difference in snow depth between control sites in the two vegetation types was indicated in early winter. Controls in *Cassiope* heath accumulated more snow than controls in *Dryas* meadow (Figure 9). The difference was significant in the time periods mid November, when mean snow depth in *Cassiope* heath controls was 12 cm compared to 5.9 cm in *Dryas* meadow controls (F=11.617, P=0.002, ANOVA), and late November when mean snow depth was 12.7 cm and 4.7 cm respectively (W = 11.5, p-value < 0.001, Wilcoxon test).

Significant differences between the treatments could be observed already in October 2008 (Figure 7, Figure 8). Fences had accumulated significantly more snow than controls by 18th October 2007 in *Dryas* meadow (W = 38, p-value = 0.006, Wilcoxon test) and by 25th October 2007 in *Cassiope* heath (F=33.189, P< 0.001, ANOVA). Maximum snow depth observed in controls and fences during the entire study period was 40 cm and 170 cm and 55 cm and 169 cm for *Cassiope* heath and *Dryas* meadow respectively (Table 8).

Table 7 Maximum snow depth (cm) observed for the different treatments in *Cassiope* heath and *Dryas* meadow at each day of measurement. Dates when sites were completely snow free are added in the last row.

Date	*Cassiope* heath Control (cm)	*Cassiope* heath Fence (cm)	*Dryas* meadow Control (cm)	*Dryas* meadow Fence (cm)
03.10.2007	20	25	5	25
10.10.2007	25	50		
18.10.2007			15	80
25.10.2007	30	125		
02.11.2007			10	
15.11.2007			15	130
19.11.2007	24	105		
28.11.2007	28	148		
06.12.2007			14	135
18.01.2008	21	170		
05.02.2008			35	133
12.02.2008			34	157
28.02.2008	32	137		
06.03.2008	39	151		
07.03.2008			47	153
26.03.2008			35	152
01.04.2008			50	157
02.04.2008	35	153		
06.05.2008			55	155
14.05.2008			46	169
20.05.2008	40	168	45	167
30.05.2008	26		25	
04.06.2008	7		10	
Snow free	6.6.2008	23.6.2008	6.6.2008	22.6.2008

Measurements of snow depth on 20th May 2008 were considered to reflect the time of maximum snow depth (Table 8). At this date the difference in maximum snow depth between controls and fences was 128 cm in *Cassiope* heath and 122 cm in *Dryas* meadow. Mean snow depth between the treatments differed significantly in both vegetation types with 98 cm in *Cassiope* heath (F= 396.3, P< 0.001, ANOVA) (Figure 7) and 108 cm in *Dryas* meadow (F= 346.13, P< 0.001, ANOVA) respectively (Figure 8). These differences in mean snow depth between control and fence sites prior to snow melt correspond to snow water equivalents of 434 mm and 478 mm for *Cassiope* heath and *Dryas* meadow respectively, when calculated based on the mean snow density of

443 kg m^{-3} measured at one of the *Dryas* meadow sites 6th May 2008 (Delmas L., unpublished).

Table 8 Comparison between maximum snow depth (cm) observed in the different vegetation types and treatments during the entire study period (with date of observation in brackets) and maximum snow depth as well as mean snow depth observed the 20.5.2008.

	Cassiope heath Control (cm)	*Cassiope* heath Fence (cm)	*Dryas* meadow Control (cm)	*Dryas* meadow Fence (cm)
Max. snow depth observed	40(20.5.2008)	170(18.1.2008)	55(6.5.2008)	169(14.5.2008)
Max. snow depth 20.5.2008	40	168	45	167
Mean snow depth 20.5.2008	32	130	21	129

Snow fences influenced snow accumulation to a distance of more than 8 m behind the fences. Snow depth measurements 20th May 2008 (Appendix B.2 Table 23) showed that behind one out of three fences in sites A and D snow depth decreased significantly with distance in the interval 2 m to 8 m behind the particular fence. Mean snow depth at 8 m distance behind these fences still exceeded the observed maxima of snow depth at control sites in the corresponding vegetation type (Table 7) with 69 cm and 78 cm for site A and D respectively. Contrary to this finding behind one out of three fences at site C and one out of three fences at site B snow depth increased significantly with distance from 2-8 m behind the particular fences (Appendix B.2 Table 23).

At sites with artificially increased snow accumulation the date of complete melt out of collars in spring was delayed by 17 and 16 days in *Cassiope* heath and *Dryas* meadow respectively (Table 7).

4.3.3 Soil temperature

In beginning of October the strong diurnal variations in hourly surface soil temperatures started to disappear and during the first month of the winter season soil temperatures between control and fence sites started to diverge from each other in both vegetation types (Appendix B.1.2 Figure 16).

Mean surface soil temperatures for the different treatments and vegetation types in the period 2.10.2007-29.5.2008 were -7.2 ºC and -2.8 ºC in control and fence sites in *Cassiope* heath and -9.0 ºC and -3.6 ºC in the according sites in *Dryas* meadow. In late winter, mean surface soil temperatures in *Cassiope* heath and *Dryas* meadow control sites were -9.1 ºC and -11.1 ºC and hence about 5 ºC lower than in early winter (Table 9). The temperatures in sites with increased snow accumulation were -3.8 ºC in *Cassiope* heath and -4.3 ºC in *Dryas* meadow, about 2 ºC lower than in early winter (Table 9). Mean soil temperatures at 5 cm depth deviated at most with 1.1 ºC from mean surface soil temperatures (Table 9).

Both in early and late winter surface soil temperatures in controls and fence sites were significantly higher in *Cassiope* heath than in *Dryas* meadow (Controls early winter: W = 127702.5, p-value < 0.001, Fences early winter: W = 74192, p-value < 0.001, Controls late winter: W = 340729.5, p-value < 0.001, Fences late winter: W = 192202, p-value < 0.001, Wilcoxon tests) (Figure 9, Figure 10). In early winter mean surface soil temperature in controls in *Cassiope* heath was 1.1 ºC higher than in *Dryas* meadow. The difference in mean soil surface temperature for fence sites in this period was 1 ºC. In late winter mean surface soil temperature in controls in *Cassiope* heath was 2 ºC higher than in *Dryas* meadow. The difference in mean soil surface temperature for fence sites in this period was 0.5 ºC (Table 9).

Soil temperatures differed significantly between the treatments in both vegetation types (Table 9, Figure 7, Figure 8). In early winter mean surface soil temperature in *Cassiope* heath controls was 2.8 ºC lower than in fence sites (W = 31370.5, p-value < 0.001, Wilcoxon test). In late winter the difference between the treatments in *Cassiope* heath was 5.3 ºC (W = 48443.5, p-value < 0.001, Wilcoxon test). Mean surface soil temperature in *Dryas* meadow controls was 2.2 ºC lower than in fence sites in early winter (W = 44294, p-value < 0.001, Wilcoxon test). This difference between the treatments increased to 6.8 ºC in late winter (W = 74598, p-value < 0.001, Wilcoxon test). The maximum difference in mean daily surface soil temperatures between the treatments was 10.8 ºC on 3rd February 2008 in *Cassiope* heath and 17.2 ºC on 21st March 2008 in *Dryas* meadow.

Table 9 Means of hourly recorded soil temperatures (ºC) in early winter (2.10.-31.12.2007) and late winter (1.1.-29.5.2008) both at surface and in 5 cm depth in the different treatments and vegetation types.

	Cassiope heath		*Dryas* meadow	
	Control (ºC)	Fence (ºC)	Control (ºC)	Fence (ºC)
Early winter (surface)	-4.1	-1.3	-5.5	-2.3
Early winter (5 cm)	-3.9	-0.5	-4.4	-1.9
Late winter (surface)	-9.1	-3.8	-11.1	-4.3
Late winter (5 cm)	-9.2	-2.8	-10.7	-4.7

The lowest mean daily surface soil temperatures for both vegetation types and treatments were recorded in the period 27.3.-12.4. 2008 (Figure 7, Figure 8). Minimum mean daily surface soil temperature in *Dryas* meadow was -23.0 ºC in control and -7.6 ºC in fence sites. Minimum mean daily surface soil temperature in *Cassiope* heath was -16.9 ºC in control and -7.0 ºC in fence sites.

Increased snow depth did not only maintain higher, but also temporally more consistent soil temperatures (Figure 7, Figure 8).

4.3.4 Winter warming event

A sudden winter warming event occurred over New Year 2007/2008 with rapidly increasing air temperatures from -12.7 ºC (31.12.2008) to 2.8 ºC (1.1.2008). This rise in temperature was accompanied by precipitation (Figure 5). Air temperatures stayed above freezing point until 3rd January when temperatures again dropped to -6.9 ºC. The effect of increased air temperatures varied between the vegetation types and treatments. Maximum hourly surface soil temperatures recorded during the warm event were 0.4 ºC and 0.1 ºC in control sites of *Cassiope* heath and *Dryas* meadow and 0.1 ºC and 0.3 ºC in fence sites in *Cassiope* heath and *Dryas* meadow respectively. Surface soil temperatures in *Cassiope* heath stayed above -1 ºC for 3 days in control sites and for 25 days in fence sites. Controls in *Dryas* meadow experienced soil surface temperatures above -1 ºC for less than 24 hours, whereas temperatures in fence sites stayed above -1 ºC for 10 days (Figure 7, Figure 8).

As a result of this warm spell, an ice layer, which persisted throughout the entire winter (Table 10) was formed on the soil surface in control sites. Mean thickness of the soil surface ice layer in *Cassiope* heath controls on 18th January 2008 was 6 cm. In *Dryas* meadow controls mean thickness of the ice layer was 8.5 cm on 12th February 2008 (Table 10).

Table 10 Mean thickness of soil surface ice layer (cm) in control sites in *Cassiope* heath and *Dryas* meadow at different times during winter 2008. Standard errors of the means are indicated in brackets. For numbers of observations see Appendix D.2 Table 27.

Date	*Cassiope* heath Control (cm)	*Dryas* meadow Control (cm)
18.01.2008	6.0 (±1.1)	
12.02.2008		8.5 (±1.6)
26.03.2008		8.0(±2.5)
14.05.2008		6.7(±2.3)
20.05.2008	5.8(±0.5)	6.8(±1.2)
30.05.2008	10.1(±1.0)	7.5(±0.8)
04.06.2008	6.0(±0.6)	10.0(±0.0)

The ice layer did not occur in sites with artificially increased snow accumulation where the warm event caused formation of ice lenses in the snow pack instead. However, there was one exception. Behind fence D10 (Appendix A.1 Figure 15) in one row of three collars (D10-1, D10.2 and D10-3) where snow depth did not exceed 26 cm (Table 11) prior to the warm event, an ice layer on the soil surface was formed. This ice layer had a mean thickness of 18 cm on 26th March 2008. Above all three collars (D10-4, D10-5, D10-6) in the second row behind this fence snow depth ranged from 94 cm to 130 cm prior to the warm event (Table 11) and these collars stayed ice free.

Table 11 Snow depth (cm) obtained by digging down to the six collars behind fence D10. Note the difference in snow depth at collars D10-1-3 compared to D10-4-6 on 6.12.2007 prior to the warming event. Snow depth at collars D10-1, D10-2 and D10-3 was not measured on 12.2.2008.

	Collars in row 1			*Collars in row 2*		
Date	D10-1 (cm)	D10-2 (cm)	D10-3 (cm)	D10-4 (cm)	D10-5 (cm)	D10-6 (cm)
03.10.2007	20	10	5	25	5	10
18.10.2007	25	3	3	30	65	10
15.11.2007	40	18	8	95	130	85
06.12.2007	26	14	12	124	130	94
12.02.2008	not meas.	not meas.	not meas.	156	143	114
26.03.2008	144	121	95	152	139	120
14.05.2008	152	117	117	169	146	123

On sites which were covered by ice the need to break through the ice layer before CO_2 efflux could be assessed, led to difficulties in estimating ecosystem respiration. The development of CO_2 efflux with time after ice layer break-through, studied on one collar on 12th February and 14th May 2008 respectively and on two collars on 26th March, revealed non-steady state conditions caused by breaking through the ice (Figure 13). CO_2 efflux values on collars immediately measured after breaking through the ice exceeded measured effluxes in summer time. The highest efflux measured directly after break-through was 5.68 µmol CO_2 m^{-2} s^{-1} on 14th May 2008. Efflux measured directly after break-through on 12th February 2008, 40 days after formation of an ice layer, was 3.91 µmol CO_2 m^{-2} s^{-1}. CO_2 efflux decreased with time and stabilized at levels of 0.25 µmol CO_2 m^{-2} s^{-1} around 230 minutes after break-through of the ice layer the 12th February. Efflux measured 20 hours after ice layer break-through on 26th March was 0.08 µmol CO_2 m^{-2} s^{-1} and 0.12 µmol CO_2 m^{-2} s^{-1} on the respective collars (Figure 13). The date of formation of and breaking through the ice layer were known and it was therefore possible to estimate the amount of gas that had been produced in this time period. Conservatively assuming that the ice layer had been a complete seal (van Bochove et al., 2001) and that no CO_2 was released during hacking through the 8.5 cm thick ice (Table 10), I integrated the exponential regression fit for the measured decrease in efflux. Prior to the calculations the measured values were transformed to the unit g C m^{-2} d^{-1} (Appendix C.1.2) and the best fitting regression ($y=2.3786e^{(-12.763x)}$; $R^2=0.94$, for the decrease in efflux measured on 12th February) was then integrated over one day. In this way the amount of CO_2 that had been trapped under the ice since the ice layer was formed was estimated to 0.19 g C m^{-2}. Evenly distributed over the 40 days of ice cover this indicates a mean CO_2 production of about 0.005 g C m^{-2} d^{-1}.

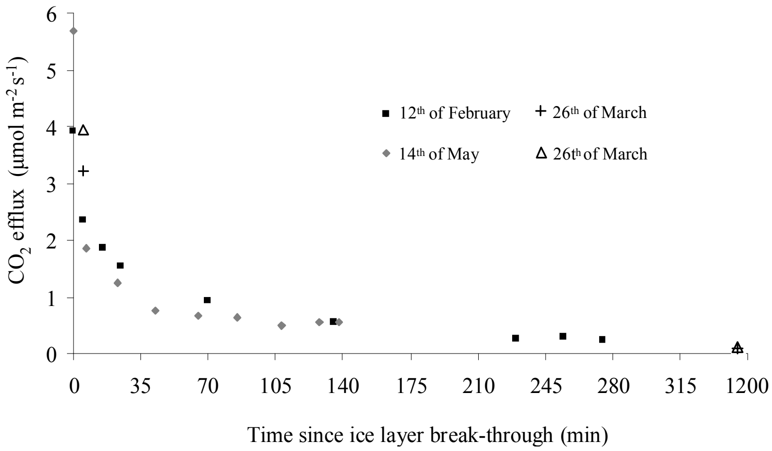

Figure 13. CO_2 efflux measured on 12th February, 26th March and 14th May 2008 at four collars at different times after breaking through the ice that covered them. For conversion of used efflux units see Appendix C.1.2.

Due to the apparent CO_2 bursts, efflux values obtained on collars which were broken free from ice less than one day before measurement were excluded from further analysis.

4.3.5 CO_2 efflux

The lowest CO_2 effluxes recorded in this study were measured during winter time with the lowest mean daily efflux of 0.05 g C m^{-2} d^{-1} measured on 23rd March 2008 in *Dryas* meadow control sites (Figure 8). Mean measured efflux was higher in early winter than in late winter in all treatments and vegetation types (Table 5, Figure 7, Figure 8). In early winter mean CO_2 efflux was 0.27 g C m^{-2} d^{-1} in controls in *Cassiope* heath and 0.33 g C m^{-2} d^{-1} in fence sites in the same vegetation type. Mean effluxes in *Dryas* meadow were 0.35 g C m^{-2} d^{-1} in control and 0.42 g C m^{-2} d^{-1} in fence sites respectively. In late winter mean CO_2 efflux was 0.2 g C m^{-2} d^{-1} and 0.32 g C m^{-2} d^{-1} in control and fence sites in *Cassiope* heath and 0.11 g C m^{-2} d^{-1} and 0.17 g C m^{-2} d^{-1} in *Dryas* meadow in control and fence sites respectively.

In both vegetation types the difference in mean CO_2 efflux between controls and fences was most pronounced for the last day of measurement (28th November and 6th December 2007) in early winter (Figure 7, Figure 8), when soil temperatures differed more than 4 °C and when numbers of replicates were relatively high (Appendix B.3 Table 24, Table 25). A trend towards higher effluxes in fence sites compared to controls both in *Cassiope* heath, where respiration in fence sites was 0.33 g C m^{-2} d^{-1} and hence almost twice as high as in controls (W = 23, p-value = 0.057, Wilcoxon test) and in *Dryas* meadow, where respiration was 0.3 g C m^{-2} d^{-1} and almost three times as high in fence sites (W = 52, p-value = 0.061, Wilcoxon test) was indicated. In late winter the amount of replicates was low and for this reason no statistical evaluations were carried out, still a trend towards higher effluxes in fence sites was visible (Figure 7, Figure 8, Appendix B.3 Table 24).

No significant difference in effluxes between the vegetation types could be observed (Figure 9, Figure 10).

4.4 Spring

Spring season lasted from 30th May to 22nd June 2008. Mean air temperature and total precipitation in this period were 2.3 ºC and 0.6 mm respectively (Figure 5).

4.4.1 Soil temperature and moisture

4.4.1.1 *Soil moisture*

As described in section 3.8 spring lasted until 2nd July 2008 for soil moisture analysis. During the days 23rd June-2nd July additional 6.1 mm of precipitation were recorded.

Soil moisture content at the end of snow-melt (Table 7) in the period 19th June-2nd July 2008 was significantly higher both in control sites (t = 2.961, df = 18.767, p-value = 0.008, T-test) (Figure 9) and fence sites (t = -2.78, df = 25.998, p-value = 0.01, T-test) (Figure 10) in *Dryas* meadow compared to the same treatments in *Cassiope* heath (Table 2).

Sites with increased snow accumulation were significantly moister than the corresponding controls both in *Dryas* meadow (t = -5.152, df = 25.916, p-value < 0.001, T-test) (Figure 8) and in *Cassiope* heath (t = -6.219, df = 19.281, p-value < 0.001, T-test) (Figure 7).

In all treatments and vegetation types soil moisture was highest on the first day of measurement and lowest at the end of this period (Figure 7, Figure 8). Mean soil moisture on 19th June 2008 in *Dryas* meadow was 80.7 % in fence sites and 52.9 % in control sites. On 2nd July soil moisture values were 50.6 % and 36.9 % respectively (Figure 8). In *Cassiope* heath according values were 70.6 % and 39.3 % on 19th June and 47.7 % and 35.2 % on 2nd July in fence and control sites respectively (Figure 7).

Soil moisture measurements in control sites on 6th June, when soils were still partly frozen and the amount of replicates therefore low (Appendix D.3 Table 28), indicate a mean soil moisture content of 67.5 % in *Cassiope* heath and 58.6 % in *Dryas* meadow respectively (Figure 7, Figure 8). In the following 13 days soil moisture decreased strongly.

4.4.1.2 Soil temperature

Mean daily air temperature increased to above 0 ºC on 26th May 2008 (Figure 5). Following elevated air temperatures, mean daily surface soil temperatures started to rise to above 0 ºC on 30th May in control sites in *Dryas* meadow and on 31st May in *Cassiope* heath controls (Table 1). In fence sites mean daily surface soil temperatures increased to above 0 ºC on 1st June as well as on 13th June in *Dryas* meadow and *Cassiope* heath respectively (Table 1). Compared to the rise in soil surface temperatures the increase of soil temperatures at 5 cm depth was delayed with 7 and 9 days in *Cassiope* heath and *Dryas* meadow controls and with 9 and 22 days in *Cassiope* heath and *Dryas* meadow fences respectively (Appendix B.1.2 Table 22).

An extended thaw period could be noticed in sites with increased snow accumulation. The number of days in which soil surface temperature stayed in the temperature interval -0.5 ºC to +0.5 ºC were 5 and 4 days in controls in *Cassiope* heath and *Dryas* meadow and 17 and 14 days in fence sites in *Cassiope* heath and *Dryas* meadow respectively (Figure 7, Figure 8).

Also the time when study sites were completely melted out differed between the treatments. All collars in control sites in *Dryas* meadow and *Cassiope* heath were snow free on 6th June, whereas all collars in fence sites in *Dryas* meadow and *Cassiope* heath were not snow free until 22nd and 23rd June respectively (Table 7).

In response to the delayed snow melt, differences in mean surface soil temperature could be observed. Surface soil temperature in spring was significantly lower in fence sites compared to controls in both vegetation types (*Cassiope* heath: $W = 7172$, p-value < 0.001; *Dryas* meadow: $W = 12703$, p-value < 0.001, Wilcoxon test) (Figure 7, Figure 8). Mean surface soil temperature was 0.3 ºC for *Cassiope* heath fence sites and 0.5 ºC in the according sites in *Dryas* meadow. Soil temperatures at 5 cm depth were as much as 3.4 ºC lower than surface soil temperatures in control sites and as much as 1.1 ºC lower than soil surface temperatures in fence sites (Table 12).

Table 12 Means of hourly recorded soil temperatures (ºC) in the period 30.5.2008-22.6.2008 both at surface and in 5 cm depth in the different treatments and vegetation types. For amount of loggers per vegetation type and treatment see B1.1 Table 19.

	Cassiope heath		*Dryas* meadow	
	Control (ºC)	Fence (ºC)	Control (ºC)	Fence (ºC)
surface	3.3	0.3	4.0	0.5
5 cm depth	0.9	-0.3	0.6	-0.6

Mean surface soil temperature for control sites in *Cassiope* heath and *Dryas* meadow in the period 30th May 2008-22nd June 2008 was 3.3 ºC and 4.0 ºC respectively (Table 12). Control sites in *Dryas* meadow experienced significantly higher surface soil temperatures than controls in *Cassiope* heath ($W = 6129$, p-value $= 0.047$). This difference was most pronounced during the first nine days in June 2008 (Figure 9). No significant differences in soil temperature between the fence sites could be observed during spring time (Figure 10).

4.4.2 CO_2 efflux

A new ice layer formed during the snow melt period in spring (Table 10) and as a result several measured efflux values had to be excluded due to high “burst-out” values after breaking through the ice (4.3.4). Mean measured CO_2 efflux during spring in control sites was 0.71 g C m^{-2} d^{-1} in *Cassiope* heath and 0.89 g C m^{-2} d^{-1} and in *Dryas* meadow (Figure 9).

Fence sites in both vegetation types were measured on 19th June and effluxes were 0.7 g C m^{-2} d^{-1} and 0.85 g C m^{-2} d^{-1} in *Cassiope* heath and *Dryas* meadow (Figure 10).

4.5 Temperature sensitivity and respiration models

The temperature sensitivity of respiration (Q_{10}) differed between the vegetation types and was generally higher in *Dryas* meadow than in *Cassiope* heath, both for respiration correlated to surface soil temperature without separating temperature into the intervals above and below 0 ºC and for correlations made for each of these two intervals separately (Table 13). The only exception was a particularly high Q_{10} of 12.9 in *Cassiope* heath fence sites for temperatures below 0 ºC. Temperature sensitivity in all treatments and vegetation types varied from nearly two-fold to up to seven-fold higher values at temperatures below 0 ºC (Table 13). For temperatures above freezing, 39-79 % of the variation in efflux could be explained solely by surface soil temperature variations. For temperatures below freezing variations in surface soil temperature could explain 54-73 % of the variation in respiration in all sites except for fences in *Cassiope* heath. Here the correlation was with around 9 % quite poor (Appendix C.3 Figure 18).

Ecosystem respiration showed stronger correlation with soil surface temperature in both treatments in *Dryas* meadow compared to the according treatments in *Cassiope* heath (Table 13).

Table 13 Q_{10} values for control and fence sites in *Cassiope* heath and *Dryas* meadow. This is the Q_{10} value for the overall observed temperature range. $Q_{10} < 0°C$ and $Q_{10} > 0°C$ are Q_{10} values for soil temperatures below and above 0°C respectively and $(Q_{10}<0°C)/(Q_{10}>0°C)$ is the ratio between these two. Numbers in brackets present R^2 values for the correlation between the exponential regression of van`t Hoff type and observed effluxes (Appendix C.3 Figure 18).

Vegetation type	Treatment	Q_{10}	$Q_{10} < 0°C$	$Q_{10} > 0°C$	$(Q_{10}<0°C)/(Q_{10}>0°C)$
Cassiope	Control	2.7 (0.78)	3 (0.54)	1.8 (0.39)	1.7
heath	Fence	3 (0.67)	12.9 (0.09)	1.8 (0.55)	7.2
Dryas	Control	4.3 (0.84)	8.7 (0.62)	4.4 (0.75)	2
meadow	Fence	3.9 (0.88)	8.3 (0.73)	2.1 (0.79)	3.9

Modelled ecosystem respiration (3.5) fitted well with the observed effluxes (Figure 7, Figure 8). Excluding spring time values, for *Dryas* meadow controls and fences 94 % and 93 % and for *Cassiope* heath controls and fences 84 % and 77 % of the observed variation in CO_2 efflux could be explained by the models (Appendix C.3 Figure 19). Mean modelled effluxes for the different seasons of the year 30.7.2007-29.7.2008 were mostly lower than mean measured effluxes, with the largest underestimates occurring in summer 2007 of the modelled year (Table 14). Modelled effluxes for the only two days on which summer measurements in the year 2007 were actually undertaken (10th July and 11th July), fitted better with the effluxes measured on these days, but still underestimated those (Table 14).

Table 14 Mean modelled ecosystem CO_2 efflux (g C m^{-2} d^{-1}) for two days of measurement in summer field season 2007 as well as for the different seasons of the modelled year 30.7.2007-29.7.2008. Numbers in brackets present deviation from mean measured ecosystem CO_2 efflux during the field seasons of this study (Table 5). The model is based on separate Q_{10} values above and below freezing Table 13.

	Cassiope heath		*Dryas* meadow	
	Control	Fence	Control	Fence
Season	Mean ecosystem CO_2 efflux (g C m^{-2} d^{-1})			
10.7.-11.7.2007	0.92 (-0.42)	1.07 (-0.31)	1.96 (-0.33)	1.54 (-0.35)
Summer 2007-19 days	0.83 (-0.51)	0.96 (-0.42)	1.52 (-0.77)	1.33 (-0.56)
Autumn days-45 days	0.54 (-0.11)	0.58 (-0.1)	0.54 (-0.23)	0.76 (-0.07)
Early winter-91 days	0.24 (-0.03)	0.29 (-0.04)	0.25 (-0.1)	0.38 (-0.04)
Late winter-150 days	0.14 (-0.06)	0.18 (-0.14)	0.11 (±0)	0.26 (+0.09)
Whole winter	0.17(-0.08)	0.22 (-0.11)	0.16 (-0.05)	0.31 (0.04)
Spring-24 days	0.59 (-0.12)	0.49 (-0.21)	0.85 (-0.04)	0.71 (-0.14)
Summer 2008-37 days	0.78 (+0.11)	0.9 (+0.06)	1.33 (-0.03)	1.22 (+0.01)
Mean annual efflux	0.34	0.39	0.44	0.54

The release of CO_2 in *Cassiope* heath controls during spring was only weakly correlated to surface soil temperatures as respiration models did not explain more than 19 % of the observed variation in effluxes (Figure 14, Figure 9). Contrary to that 82 % of the variation of measured effluxes in *Dryas* meadow controls during spring could be predicted by the model based on surface soil temperature variations (Figure 14, Figure 9).

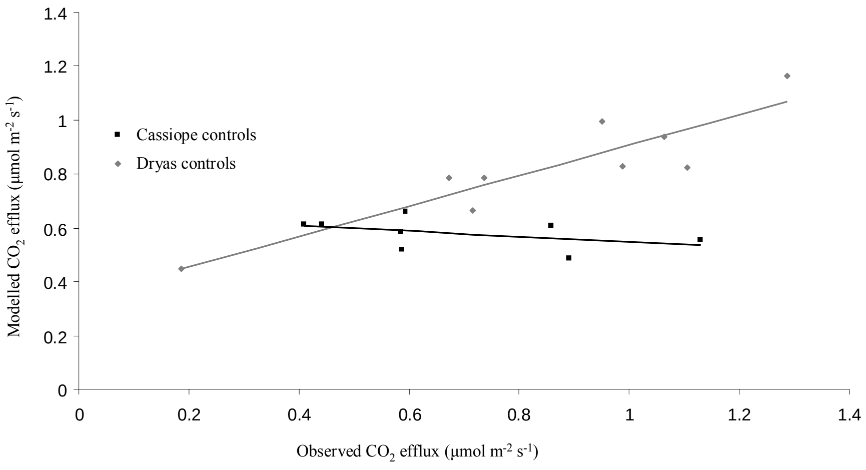

Figure 14. Modelled versus observed CO_2 efflux in *Cassiope* heath and *Dryas* meadow controls in spring 2008. Linear regression fits are shown as lines. Corresponding R^2 values are 0.19 and 0.82 for *Cassiope* and *Dryas* meadow controls respectively. For numbers of replicates for each data point see Appendix B.3 Table 25.

Annual CO_2 efflux was higher in both treatments in *Dryas* meadow than in *Cassiope* heath (Table 15, Figure 9, Figure 10). Compared to control sites annual efflux in fence sites increased with 14.8 % and 21 % in *Cassiope* heath and *Dryas* meadow respectively (Table 15).

Table 15 Ecosystem CO_2 efflux (g C m^{-2}) as sum of daily modelled effluxes for summer, autumn, winter and spring season in the year 30.7.2007-29.7.2008. Deviation from Table 14 is due to rounding of mean modelled efflux values in that table. Numbers in brackets present the contribution of each season to the total annual efflux. Values in italics present winter efflux and annual efflux modelled with Q_{10} values for the overall observed temperature range reported in Table 13.

	Cassiope heath		*Dryas* meadow	
	Control	Fence	Control	Fence
Season	Ecosystem CO_2 efflux (g C m^{-2})			
Summer 2007/08	44.8	51.8	77.9	70.5
	(35.7 %)	(36 %)	(48 %)	(35.9 %)
Autumn	24.4	26.3	24.3	34.4
	(19.5 %)	(18.3 %)	(15 %)	(17.5 %)
Whole winter	**41.9**	**54.1**	**39.7**	**74.4**
	(33.4 %)	(37.6 %)	(24.5 %)	(37.9 %)
Spring	14.3	11.7	20.3	16.9
	(11.4 %)	(8.1 %)	(12.5 %)	(8.6 %)
Annual efflux	**125.4**	**143.9**	**162.1**	**196.2**
Winter efflux	*46.1*	*74.5*	*39.5*	*70.4*
Annual efflux	*124.4*	*157.3*	*165.2*	*182.0*

Respiration during the growing season accounted for about 36 % of the annual efflux in all sites except for control sites in *Dryas* meadow where respiration contributed 48 % to the total annual efflux (Table 15).

Winter respiration contributed 33.4 % and 24.5 % to annual ecosystem respiration in *Cassiope* heath and *Dryas* meadow controls. Winter time efflux behind the fences was about 38 % of the annual efflux in both vegetation types. Whereas winter time efflux in fence sites in *Cassiope* heath increased with 29 % compared to controls, the increase in winter time efflux was 87 % in fence sites in *Dryas* meadow compared to controls (Table 15).

4.6 Biomass

No significant difference in the amount of total biomass between *Cassiope* heath and *Dryas* meadow and between the treatments was observed, though total biomass in fence sites in *Cassiope* heath was slightly higher than in controls. In *Dryas* meadow control sites total biomass was slightly higher compared to fence sites (Table 16).

There were no significant differences in belowground biomass, neither between the two vegetation types nor between the treatments. However, a trend towards increased belowground biomass was noticed in sites with increased snow accumulation. Belowground biomass in those sites was between 11-27 % higher than in controls (Table 16).

The amount of aboveground biomass differed between the two vegetation types. Mean biomass in *Cassiope* heath controls (2306 $g_{(dryweight)} \cdot m^{-2}$) was significantly (F =18.827, P<0.001, ANOVA) lower than in *Dryas* meadow controls (3296.7 $g_{(dryweight)} \cdot m^{-2}$) (Table 16). When separating aboveground biomass into the woody plants *Cassiope tetragona* (for samples from *Cassiope* heath) alternatively *Dryas octopetala* (for samples from *Dryas* meadow) and “Rest”, including all other vascular plants and mosses, it becomes obvious that there was a vegetation type specific difference between the fraction of woody plants and “Rest” in relation to the amount of total aboveground biomass. Whereas *Cassiope tetragona* contributed 21.4 % to the amount of total aboveground biomass in *Cassiope* heath controls, *Dryas octopetala* accounted for only 5.2 % of the total aboveground biomass in *Dryas* meadow controls. The amount of biomass of other vascular plants and mosses was significantly higher in *Dryas* meadow controls (3124.1 $g_{(dryweight)} \cdot m^{-2}$) than in *Cassiope* heath controls (1812.5 $g_{(dryweight)} \cdot m^{-2}$) (F= 9.588, P= 0.005, ANOVA).

In addition to vegetation type specific differences, a significant difference between the treatments could be observed in *Dryas* meadow (Table 16). In this vegetation type, aboveground biomass was significantly lower in sites with snow fences compared to controls (W = 80, p-value = 0.02, Wilcoxon test). This was due to a significantly lower amount of other vascular plants and mosses in fence sites (F = 4.9516, P = 0.039, ANOVA), whereas the biomass of *Dryas octopetala* did not differ significantly.

Table 16 Mean biomass in $g_{(dryweight)} \cdot m^{-2}$ for the different groups *Cassiope tetragona*, *Dryas octopetala* and Rest (including all other vascular plants and mosses) as well as Belowground biomass. Aboveground biomass is the sum of *Cassiope tetragona*, *Dryas octopetala* and Rest. Total biomass is the mean sum of Aboveground and Belowground biomass. Numbers in brackets present the standard errors of the means.

	Cassiope heath Control $g \cdot m^{-2}$	*Cassiope* heath Fence $g \cdot m^{-2}$	*Dryas* meadow Control $g \cdot m^{-2}$	*Dryas* meadow Fence $g \cdot m^{-2}$
Cassiope/*Dryas*	493.5(±83.7)	590.6(±85.8)	172.5 (±30.9)	246.9 (±95.3)
Rest	1812.5 (±235.1)	1461.3 (±225.6)	3124.1 (±381.4)	2061 (±404.6)
Aboveground biomass	2306 (±253.6)	2051.9 (±226.9)	3296.7 (±386.4)	2307.9 (±388.8)
Belowground biomass	2334.8 (±319)	3183.1 (±396.1)	2575.5 (±361.1)	2903 (±401.4)
Total biomass	4640.9 (±412.6)	5235 (±416.2)	5872.2 (±516.9)	5210.9 (±591.1)

5 Discussion

5.1 Annual and cold season CO_2 efflux

CO_2 efflux in the studied region showed strong seasonality with highest effluxes being measured in summer and lowest effluxes measured in winter time. The estimated annual efflux was 125.4 g C m^{-2} yr^{-1} (*Cassiope* heath) - 162.1 g C m^{-2} yr^{-1} (*Dryas* meadow) which supports the previous annual efflux estimate of 103-176 g C m^{-2} yr^{-1} for comparable vegetation types in Endalen, a valley nearby Adventdalen (Elberling, 2007). These estimates are in the lower range of annual effluxes measured in Alaskan dry tussock tundra of 150-368 g C m^{-2} yr^{-1} (Welker et al., 2000).

The estimates of annual CO_2 efflux are based on the assumption that surface soil temperature is the only controlling factor on respiration rate throughout the year. As already described in the introduction this is not the case. However, the models based solely on soil surface temperature could explain 77-94 % of the observed annual variation in efflux (Appendix C.3 Figure 19). A comparison between mean modelled and measured effluxes showed that efflux in the different seasons was mainly underestimated by the model (Table 14). In addition it has been argued that dynamic soil chambers like the one used in this study tend to underestimate true efflux (Davidson et al., 2002) and therefore the presented values are considered to be under- rather than overestimated. Although the amount of measurements during winter was strongly limited, simple temperature based respiration models can provide valid efflux estimates for this period, as several studies have demonstrated that CO_2 efflux is strongly temperature dependent in winter time (Elberling, 2007; Goulden et al., 1996; Sullivan et al., 2008; Zimov et al., 1996).

Summarized for the 241 days long cold season, winter efflux was 39.7 g C m^{-2} (*Dryas* meadow) - 41.9 g C m^{-2} (*Cassiope* heath) and thus significantly contributed to the annual CO_2 efflux with 25-33 % (Table 15). These estimates agree well with previously published winter effluxes for arctic ecosystems of about 20-70 g C m^{-2} (Fahnestock et al., 1999; Grogan and Jonasson, 2005; Oechel et al., 1997a; Zimov et al., 1993), although other studies have stated either much lower (2 g C m^{-2}), or much higher (111-189 g C m^{-2}) winter effluxes (Fahnestock et al., 1998; Grogan and Chapin, 1999).

The contribution of winter respiration to total annual respiration was in the middle of recent estimates for boreal and arctic ecosystems spanning from 17-50 % (Elberling and Brandt, 2003; Fahnestock et al., 1999; Zimov et al., 1996). The contribution of winter efflux to annual efflux was smaller in *Dryas* meadow sites, which is consistent with that soil temperatures in winter were significantly lower than in *Cassiope* heath sites. The same pattern was found by Elberling (2007).

Effluxes were higher in early winter with about 0.2 g C m^{-2} d^{-1} than in late winter with about 0.1 g C m^{-2} d^{-1} (Table 14). These values lie within the observed variety of 0.2-0.53 g C m^{-2} d^{-1} in early winter and 0.07-0.2 g C m^{-2} d^{-1} in late winter in different tundra vegetation types in northern Alaska (Jones et al., 1999). The mean winter effluxes of 0.16 g C m^{-2} d^{-1} (*Dryas* meadow) and 0.17 g C m^{-2} d^{-1} (*Cassiope* heath) are higher than the mean winter efflux of 0.114 g C m^{-2} d^{-1} estimated in Endalen (Elberling, 2007), but comparable to mean winter effluxes in Alaskan moist tussock (0.12-0.3 g C m^{-2} d^{-1}) and dry heath tundra (0.18 g C m^{-2} d^{-1}) and to mean winter efflux reported for forest tundra in north-eastern Siberia (0.15 g C m^{-2} d^{-1}) (Fahnestock et al., 1999; Oechel et al., 1997b; Sullivan et al., 2008; Zimov et al., 1993). Nobrega and Grogan (2007) stated a winter CO_2 production of 27 g C m^{-2} over a period of 278 days (mean production of 0.1 g C m^{-2} d^{-1}) for birch hummock tundra in Northern Canada measured with soda lime traps. Studies applying this technique have yielded efflux estimates both well below and well above estimates based on measurements with snow probes and flux chambers (Sullivan et al., 2008), but the reported efflux from Northern Canada is in line with flux chamber measurements from Endalen (Elberling, 2007).

The results of different studies illustrate the uncertainties of obtained winter efflux values, which are connected not only to differences in applied methods and interannual variation (Grogan and Chapin, 1999), but also to harsh field work conditions and low efflux rates in this time period. In the present study the amount of measurements was very restricted and the standard deviation of the reported mean winter effluxes was relatively high (Appendix B.3 Table 24). Also the equipment might not have been working as accurately in cold conditions, because the flux chamber is not designed for temperatures below 0 °C (LI-COR, 2002). The uncertainty in measured effluxes can lead to large deviations when measured values are extrapolated over a whole season and compared to estimates from other studies. In order to obtain more robust efflux estimates, future studies should apply different techniques and attempt to cover longer time-periods in winter, even though field work conditions during this season are challenging.

Despite the high uncertainties in winter efflux estimates the values reported in the present study are in accordance with other studies. Still, winter emissions are considered biased, because non-steady state releases of trapped gas were not included.

5.1.1 Trapping of CO_2 under ice and pulses of CO_2 release

Observations during winter and spring indicate that some of the CO_2 produced during the cold season is trapped either under an ice-layer or in the frozen soil and released when the ice-layer is artificially broken or when ice and soil start to thaw.

CO_2 trapping beneath a frozen soil surface has been shown by Oechel et al. (1997b), who measured initial effluxes of up to 82 g C m^{-2} d^{-1} after drilling through the soil surface, a rate more than 300 times higher than effluxes measured in undrilled controls. It has also been shown that an ice layer of 10 cm can act as an impermeable barrier to gas diffusion (van Bochove et al., 2001). The measured bursts of CO_2 after breaking through the ice layer are consistent with those studies and because of the conservative assumptions made (4.3.4), the calculated amount of 0.19 g C m^{-2} is considered to present a minimum estimate and indicates that winter respiration during 40 days in January and February must have been at least 0.005 g C m^{-2} d^{-1}. CO_2 was most likely released already during breaking of the ice layer and considering the measured initial efflux values stated by Oechel et al. (1997b), it appears that the amount of gas that was actually trapped under the ice might have been higher.

In addition, pulses of CO_2 release that could not be predicted by the temperature based respiration model were observed over several days in spring time in *Cassiope* heath controls. The measured effluxes exceeded modelled ones by far and soil surface temperature could only explain 19 % of the observed variation (Figure 13). Such "bursts" related to thawing have been observed in previous field studies during spring thaw (Elberling and Brandt, 2003; Fahnestock et al., 1998; Kwon et al., 2006) as well as in incubation experiments (Elberling et al., 2008) and are suggested to represent physical release of gas that was produced und trapped during winter (ibid.) as well as enhanced soil respiration due to the death and lysis of microbes and subsequent release of nutrients into the soil solution (Skogland et al., 1988). No pulses of CO_2 release could be observed in *Dryas* meadow controls, since those bursts probably had happened in the beginning of spring and were missed, because the sequence of measurements was not as dense at this time. This argument is drawn upon the fact, that surface soil temperatures were significantly higher in *Dryas* meadow controls in the period when bursts in *Cassiope* heath were measured (Appendix B.3 Table 25). As suggested by Larsen et al. (2007) pulses of CO_2 release during spring thaw indicate that annual models based on soil temperatures underestimate effluxes in this time period.

The possibility that CO_2 can be trapped beneath an ice layer and in the soil must be considered when winter efflux measurements are evaluated, keeping in mind that measurements yield gas release rates, which might differ from actual production rates. Especially efflux values obtained by measurements on the snow surface might not be reliable for the assessment of actual gas production in the soil if an ice-layer is present. In order to increase the accuracy of winter CO_2 efflux measurements, further studies should aim for higher temporal resolution, especially in the time during spring-thaw. More accurate estimates of the amount of gas that is released during winter and spring-thaw will increase the accuracy of winter gas production estimates.

5.1.2 Temperature sensitivity of respiration

The observed correlation of respiration with temperature is in line with both studies in the field (Elberling, 2007; Grogan and Jonasson, 2005; Sullivan et al., 2008) and incubation experiments (Fang and Moncrieff, 2001; Kirschbaum, 1995). The temperature sensitivity (Q_{10}) over the whole temperature range was 2.7-4.3 and is thus in accordance with the spread of 2.2-4.1 reported for incubated soil from Ny-Ålesund (Bekku et al., 2004), but somewhat lower than the by Elberling (2007) noted range of 5-7.1. Both studies used the same calculation method as applied here, a requirement that needs to be fulfilled in order to permit comparison of Q_{10} values from different studies (Fang and Moncrieff, 2001). That Q_{10} values were lower than in a previous study carried out in the same region some years earlier (Elberling, 2007) might be a sign for interannual variability of respiration controlling factors, for example differences in soil moisture, which has been shown to influence Q_{10} values (Illeris et al., 2004a).

As demonstrated by previous studies, Q_{10} values are higher below than above freezing (Elberling and Brandt, 2003; Mikan et al., 2002). The reasons behind are still debated. Elberling and Brandt (2003) argued that the shift in Q_{10} might partly be an artefact, caused by “trapping” of some of the produced CO_2 in the soil. They could either enhance or eliminate the shift in Q_{10} by manipulating water and salt content of soil samples in the laboratory, thus increasing or avoiding freezing and subsequently physical trapping of the produced gas at subzero temperatures. Others have suggested that the change of Q_{10} reflects a shift in the influence of different controlling processes on respiration (Mikan et al., 2002) and represents barriers to diffusion caused by desiccation or lack of unfrozen water (ibid.), or limitations of substrate supply (Davidson et al., 2006).

Strong C limitation of microbial activity and growth in winter has been indicated (Brooks et al., 2005; Buckeridge and Grogan, 2008; Schimel et al., 2004) and supports the hypothesis of depletion of available organic pools during winter and resulting enhanced mortality and lysis of soil microbes (Buckeridge and Grogan, 2008). According to Buckerridge and Grogan (2008) the substrate limitation is more severe in sites under deepened snow, because in those relatively “warm” soils decomposition of organic matter is less restricted by temperature. The increase in temperature sensitivity of respiration at temperatures below freezing was much higher in fence sites (4- to 7-fold) than in control sites (about 2-fold) and supports this hypothesis (Table 13). It has been stated that a shift in microbial substrate use occurs when soil temperature is beginning to decrease. Close to 0 °C microbes start to use less nitrogen-poor plant litter and more dissolved organic matter and nitrogen-rich recycled microbial biomass and products (Schimel et al., 2004; Sturm et al., 2005). This shift in substrate use might influence Q_{10} values as well.

Also, overall correlations between respiration and temperature were less strong in *Cassiope* heath compared to *Dryas* meadow. It is known that the quality of plant litter is influencing respiration rates (Cornwell et al., 2008; Nadelhoffer et al., 1991) and that respiration in *Cassiope* heath is more limited by the lower substrate quality (expressed as higher C:N ratio) of this vegetation type (Elberling et al., 2004; Elberling et al., 2008). Substrate limitation might be reflected in the observed differences in correlation fits between the vegetation types and as shown by Larsen et al. (2007) incorporation of substrate supply in addition to temperature might increase the fit of ecosystem respiration models.

Measurements of respiration in the field cannot distinguish between root and microbial respiration. Neither can they account for the difference in respiration derived from recently fixed C and respiration derived from bulk soil organic matter (Grogan and Jonasson, 2005). Though both contribute to ecosystem respiration throughout the year, the first one is more temperature sensitive than the latter one (ibid.). Hence, Q_{10} values based on field observations reflect a sum of temperature dependences of different processes that add up to the total ecosystem respiration. Considering this complexity it is suprising how well simple models based solely on soil temperatures matched the observed variation in effluxes during the study year.

Further development of models that reach beyond simple temperature dependence of ecosystem respiration, needs to be based on studies which investigate also other driving factors and aim to evaluate how their relative influence on respiration changes, both on a temporal, but also on a spatial scale.

5.2 The effect of increased snow depth on winter soil temperatures

Increased snow accumulation behind the fences led to higher and temporally more consistent soil temperatures in winter time, which has been demonstrated by previous studies (Nobrega and Grogan, 2007; Schimel et al., 2004; Walker et al., 1999). The difference of late winter mean soil surface temperatures in sites with increased snow accumulation compared to ambient sites was between 5 and 7 ºC and thus less than the mean difference of 15 ºC measured in the snow fence experiment in Toolik Lake, Alaska (Walker et al., 1999). However, in Toolik Lake, snow fences increased snow depth from the ambient 0.5 m to about 4 m compared to a more moderate increase of snow depth with about 1 m in this study. In line with the present study, Nobrega and Grogan (2007) reported a temperature difference of 5 ºC in late winter between ambient sites covered by 0.3 m compared to snow fence sites covered by 1 m of snow. Also the recorded increase in minimum soil surface temperature of 9 ºC in the Niwot Ridge snow fence experiment (Brooks et al., 1995) is of comparable magnitude as the increase of 9.9 ºC to 15.4 ºC recorded in this study.

In addition to temperature differences between sites with increased and sites with natural snow conditions, differences between the vegetation types could be observed as well. That sites under ambient conditions in more wind-exposed *Dryas* ridges experienced lower soil temperatures than sites in *Cassiope* heath has been reported by Elberling (2007). However, in his study, the difference in snow depth between sites in *Dryas* meadow and *Cassiope* heath was much more pronounced throughout the whole winter compared to the present study, where snow depth between the control sites differed only in early winter and where sites in *Dryas* meadow were less exposed than the ones studied by Elberling (2007). Due to the occurrence of a warm event, resulting ice-layers in the snow-pack could have stabilized the snow, thus reducing wind-drift and consequently differences in snow depth between the sites in late winter. Still, the temperature difference between the sites was apparent throughout the whole winter. This might indicate that the development of the snow-pack in early winter is crucial for determining the temperature regime for all of the cold season as argued by Rønning (1969). On the other hand, sites with increased snow accumulation in *Dryas* meadow had significantly lower soil temperatures in winter time, too. Since snow depth did not differ between fence sites in the two vegetation types and fence sites in *Dryas* meadow actually had higher soil temperatures in autumn, before entering the cold season, it seems that the vegetation type itself influences soil temperatures as well. Denser vegetation can act as an insulator against heat conduction and convection (Rønning, 1969). The thicker and better developed shrub mats of *Cassiope tetragona* might have dampened the effect of decreasing temperatures resulting in higher soil temperatures in *Cassiope* heath in the cold season compared to *Dryas* meadow.

5.3 The effect of increased snow depth on soil temperature and soil moisture during spring and the growing season

The increased amount of snow and resultant prolonged thawing in spring in snow fence sites caused significant differences in soil moisture and soil temperature compared to ambient sites. Snow fence sites remained wetter and colder in spring, probably because of an increased amount of available melt water as well as a reduced energy input due to higher albedo as long as the soil was still snow covered (Elberling, 2007). The differences in soil moisture and temperature between the treatments in spring were still significant in the growing season 2008, with one exception. In *Dryas* meadow soil temperature in summer did not differ between control and fence sites.

Soil moisture was higher in both controls and fence sites in *Dryas* meadow compared to *Cassiope* heath in the first summer of this study, but not in the second summer, illustrating the interannual variability of soil moisture, probably in response to differences in snow accumulation and soil temperature. The difference might also partly be due to contrasting soil properties between the sites, which were not studied in the scope of this work, but should be considered in further investigations.

Hinkel and Hurd (2006) found that drift size behind snow fences varied significantly between the years. If this was the case also in the present study a variation in snow accumulation could have caused the noted differences in soil moisture content in fence sites in summer 2007 compared to summer 2008. Less snow accumulation and possibly earlier melt-out could also explain the absence of any difference in soil moisture between fence and control sites in *Cassiope* heath in summer 2007. However, this conclusion remains speculative, because neither winter accumulation nor snowmelt were studied in the previous year.

It is interesting to note that soil temperatures in the growing season seemed not only to be controlled by differences in snow depth in the previous winter, but once again by the vegetation type itself. No differences in surface soil temperature could be observed between the treatments in *Dryas* meadow, whereas *Cassiope* heath fence sites experienced significantly lower surface soil temperatures than controls. Moreover, *Cassiope* heath controls exhibited significantly higher and fence sites significantly lower surface soil temperatures than the according treatments in *Dryas* meadow. This pattern was neither due to malfunctioning of the data loggers (the same trends are recognizable in soil temperatures at 5 cm depth (Table 4)) nor to differences in soil moisture content, because the latter one did not differ significantly between the vegetation types.

Differences in plant morphology in combination with the wind shielding effect of the snow fences might elucidate the discrepancy in soil temperature between the vegetation types. Rønning (1969) pointed out that wind, although reduced close to the ground, is strong enough to modify soil temperature. Control sites in both vegetation types were exposed to prevailing summer winds and because *Cassiope tetragona* is growing denser and higher than the dominating plants in *Dryas* meadow it might act as a protection against heat transport due to wind, thus maintaining higher soil temperatures than in more wind exposed *Dryas* meadow. Contrary to this, in fence sites where heat transport by wind is reduced, the difference in absorption of incoming solar radiation might be the crucial factor determining differences in soil temperature. Less dense vegetation in *Dryas* meadow facilitates absorption of incoming solar radiation at the soil surface, which subsequently is warmed to a larger degree than *Cassiope* heath, where less solar radiation meets the soil surface but is absorbed by the vegetation instead.

To explain the differences in soil temperature between the treatments in the two vegetation types, soil moisture content has to be taken into account in addition to the factors already discussed. Due to the high specific heat capacity of water, a larger amount of energy is needed to increase soil temperature in sites with higher soil moisture content. Soil moisture content was higher in fence sites and soil surface temperatures should therefore have been lower in these sites compared to controls. This was only the case in *Cassiope* heath, where the vegetation is expected to have reduced heat transport by wind and therefore might have facilitated soil moisture content to be the primary factor influencing soil temperature. In contrast, in *Dryas* meadow controls lower soil moisture content promoted soil warming, but this warming might have been counteracted by the heat transport due to wind, which in turn was not influencing the fence sites. As a result soil temperatures between the treatments in this vegetation type did not differ significantly.

These results indicate that snow fences can influence summer microclimate. This means that effects of the treatment might not solely be caused by changes in snow depth, but also by alteration of climatic variables during the growing season, something that needs to be accounted for in future long-term studies at these sites.

5.4 The effect of changes in soil temperature and soil moisture conditions on winter and summer CO_2 efflux

5.4.1 Winter CO_2 efflux

The comparison of effluxes in early winter showed a strong trend towards increased efflux in sites with increased snow depth, even though measured effluxes did not differ significantly, which is probably due to the limited amount of replicates and the relatively high standard deviation (Appendix B.3 Table 24). Snow depth is known to be an important factor controlling soil temperature and thereby microbial activity in winter (Elberling, 2007; Schimel et al., 2004). The effluxes modelled in the present study indicate that the increase in winter efflux due to increased soil temperatures was between 29-87 %. However, the amount of field measurements during winter was very restricted and the modelled effluxes could not be validated for larger parts of the cold season. Still, the finding of the model is consistent with previous studies, which report increases in winter CO_2 efflux ranging from 55-100 % as a consequence of increased snow depth (Brooks et al., 1995; Nobrega and Grogan, 2007; Walker et al., 1999; Welker et al., 2000). The increase in respiration might not be entirely linked to the direct effect of soil temperature on microbial activity, but also to indirect effects such as an increased amount of unfrozen water (Brooks et al., 1995; Welker et al., 2000). In the present study, models based on soil temperatures could explain much of the observed annual variation in respiration and therefore soil temperature is assumed to have been one of the major controlling factors of respiration rates. Still, it should be pointed out that about 30 % of the microbial population is killed when soil temperatures drop below -7 ºC (Skogland et al., 1988), which was about the minimum daily surface soil temperature that fence sites experienced during winter. Soil temperatures in control sites were much lower and a greater reduction of the microbial community in those sites could also have caused reduced respiration rates (Schimel and Clein, 1996).

In order to perform a sensitivity analysis of the influence of applied Q_{10} values on the modelled efflux, annual as well as winter effluxes were also calculated with the overall Q_{10} values reported in Table 13. Annual estimates deviated with up to 9 % and winter estimates with up to 10 %, except for *Cassiope* heath fence sites where winter efflux increased with 37 % compared to the former model applied in this study. This is due to the much higher Q_{10} value below 0 °C in those sites, when Q_{10} is separately calculated for above and below freezing, which implies that a decrease in temperature leads to a greater decrease in respiration rates than it would if the Q_{10} value was smaller. This strong increase in calculated winter efflux in *Cassiope* heath fences changed the overall increase in efflux in response to enhanced snow depth to a magnitude of 62-78 % (Table 15). The calculations based on separate Q_{10} values are therefore considered to be more conservative.

In the present study the end of winter was defined as the day when the first study sites experienced above freezing temperatures (which happened to be control sites in *Dryas* meadow). Considering that temperatures did not rise above freezing for additional 15 and 2 days in fence sites in *Cassiope* heath and *Dryas* meadow respectively (Table 1) and that winter in those sites therefore lasted longer than assumed (Table 14, Table 15), the increase in winter respiration in fence sites compared to controls would have had a even higher magnitude of 41-90 %.

These results indicate that changes in precipitation pattern and subsequent increases in snow depth can lead to substantial increases in winter respiration in arctic ecosystems. It is important to point out that an increase in precipitation does not necessarily lead to deeper snow, because snow depth especially in arctic tundra regions, is controlled as much by wind as by variations in the amount of precipitation (Sturm et al., 2001). However, if climate warming leads to the expected increase in shrub size and abundance, as already observed in Alaskan tundra (Sturm et al., 2005), more snow could be trapped by the vegetation and snow depth might increase even in wind-exposed habitats (Sturm et al., 2001).

5.4.2 Summer CO_2 efflux

As expected, measured respiration rates were highest during summer. Effluxes in the growing season 2007 exceeded rates in 2008, which might partly be due to a restricted amount of measurements in the first summer, but is also caused by differences in soil temperatures, which in 2008 never reached the level of 2007. In summer 2007 measured respiration rate in *Dryas* meadow was comparable to the mean efflux of 2.3 g C m^{-2} d^{-1}

in summer 2003 and 2004 in a similar vegetation type nearby (Sjögersten et al., 2006) and CO_2 efflux in *Cassiope* heath was in the range of previously reported rates of 1-2.1 g C m^{-2} d^{-1} in the same vegetation type in Zackenberg, Greenland (Christensen et al., 2000) (Table 5). Growing season respiration was lower in the following year, but slightly higher than the rate of 0.54-0.87 g C m^{-2} d^{-1} measured by Elberling et al. (2008) in July and August 2001 in Greenland.

Negative correlations of respiration with soil moisture and positive correlations with soil temperature were observed in all sites. Sjögersten et al. (2006) found that ecosystem respiration increased with soil moisture content across a gradient from xeric to moist sites in the same area, whereas Oechel et al. (1993) indicated that dry conditions enhanced CO_2 efflux in Alaskan tundra. These findings seem contradicting, but might actually complement each other. As stated by Elberling et al. (2008) respiration decreases when soil moisture content is above or below a certain optimum range (12-35 % at 26 °C) either due to the lack of air-filled pore space or due to the lack of available water. Approaching this optimum from either side would result in two contrasting statements. In the present study, soil moisture content did never reach the lower end of the optimum and therefore a negative correlation with respiration was observed.

Although soil moisture and, except in *Dryas* meadow, also soil temperature conditions differed significantly between the treatments, CO_2 efflux did not. Similar respiration rates despite more favourable conditions in control sites might indicate differences in factors others than soil temperature and soil moisture. For example, relatively decreased respiration in controls could be due to the negative effect of surface ice-layers on the soil microarthropod communities. Microarthropods consume plant litter and excrete fecal pellets which are easier to metabolize than the original litter, thus enhancing decomposition (Bardgett, 2005). These animals can be reduced in numbers by 50 % in sites where surface ice-layers occur (Coulson et al., 2000). Also, a decrease in leaf C:N ratio (5.5) as an effect of more snow (Walsh et al., 1997) might lead to relatively increased respiration rates in fence sites, despite lower soil temperature and higher moisture content. Moreover, previous studies have stated that increased snow depth can alter the soil nitrogen pool (Brooks et al., 1997; Nobrega and Grogan, 2007; Schimel et al., 2004) and thus may lead to increased microbial biomass and changes in the relation between fungal and bacterial biomass as well as in the bacterial community structure (Rinnan et al., 2007).

The conclusion that other factors than solely soil temperature and soil moisture are influencing growing season respiration is supported by the fact that significant differences in CO_2 efflux were noticed between the vegetation types, which were not related to differences in soil moisture and soil temperature conditions.

Growing season efflux in fence sites was not decreased compared to controls, indicating that effects of increased snow depth on annual CO_2 efflux would be determined by changes in winter respiration rate. This implies that further research on the impact of increased winter precipitation on ecosystem respiration in the Arctic should put more focus on measurements during the cold season.

5.5 The effect of vegetation type on summer CO_2 efflux

This section will concentrate on control sites in order to not confuse any difference in response to the snow treatment between the two vegetation types with naturally occurring differences between them.

Summer respiration rates differed significantly between the vegetation types and were higher in *Dryas* meadow than in *Cassiope* heath, even though no differences in soil moisture were noted and soil temperature was actually higher in *Cassiope* heath. Hence, vegetation type itself seems to be the major control on summer respiration, a conclusion supported by Grogan and Chapin (1999), who stated that vegetation type is not affecting winter respiration rates, but is the primary controlling factor during summer.

There are several vegetation type specific factors that might influence respiration rate such as soil microclimate and structure, the amount and quality of detritus and the rate of root respiration (Raich and Tufekcioglu, 2000). Root respiration is a main contributor to total soil respiration in the growing season (Billings et al., 1977) and plant specific differences in root respiration rate have been observed (Cooper, 2004). Moreover Nadelhoffer (1991) stated that differences in soil respiration were due to differences in carbon quality rather than temperature. C:N ratio and initial lignin concentrations control decomposition rates and deciduous shrub and graminoid leaf litter decompose faster than leaf litter from evergreen shrubs (Cornwell et al., 2008; Robinson and Wookey, 1997). C:N ratios have been shown to be higher in leaf litter of *Cassiope tetragona* than *Dryas octopetala* (Elberling et al., 2008) and in addition the fraction of more easily decomposable non-woody plants was higher in *Dryas* tundra sites of this study. It has also been indicated that soils beneath *Cassiope tetragona* have lower soil organic carbon stocks than soils under *Dryas octopetala* (Elberling, 2007).

Macroinvertebrates are lacking on Svalbard and the most important soil decomposers are bacteria, fungi and microarthropods (Elvebakk, 1997). Coulson et al. (2003) did not find significant differences in density of soil microarthropods associated with *Cassiope tetragona* and *Dryas octopetala* growing within one plant community on Svalbard, but stated that these plant species could be associated with distinct communities of soil microarthropods. In addition Väre et al. (1992) found that root associated fungi differed between *Cassiope tetragona*, having ericoid mycorrhizae and *Dryas octopetala*, having ectomycorrhizal partners. Moreover, studies have shown that soils in *Cassiope tetra-*

gona and *Dryas integrifolia* (a plant species similar in its ecology to *Dryas octopetala*, (Rønning, 1965) dominated sites differed in microbial community structure (Deslippe and Egger, 2006).

It seems likely that the mentioned factors contributed to the observed differences in respiration rate between the vegetation types. To gain a deeper understanding of the variables that influence respiration year-round, further studies should aim to investigate other factors than solely soil temperature and soil moisture.

5.6 The effect of increased snow cover on plant growth

The aboveground biomass estimates in this study are considerably higher than in a previous study from Adventdalen, where mean standing crop biomass in *Cassiope* heath was estimated to 99 $g_{(dryweight)} \cdot m^{-2}$ (Wegener and Odasz-Albrigtsen, 1998). This overestimation can be due to several factors. Firstly, the sampled collars enclose a very small area and it is known that sampling in too small areas leads to large measurement biases (Coulloudon et al., 1996). Secondly, collars were always placed in vegetated patches resembling full coverage, whereas the vegetation cover in the region is not continuous. Thirdly, I did not differentiate between dead and alive biomass and thus included dead plant parts in the reported biomass estimates. In any case, for the scope of this study it was sufficient to evaluate relative differences between the vegetation types and treatments and although biomass values were overestimated, the error was the same for all samples and therefore possible trends remain recognizable.

The start of the growing season was delayed for 16-17 days in snow fence sites, which is in line with the observed delayed snow melt of 2-3 weeks in sites with increased snow depth in Alaskan tussock tundra (Walker et al., 1999). Plants might be able to compensate for a delayed start of the growing period as shown by other studies, which found that even though the growing season was shortened, vegetation growth increased in sites with enhanced snow depth (Scott and Rouse, 1995; Wahren et al., 2005; Walker et al., 1999). Still, Walker et al. (1999) argued that arctic plants could endure a shortened year, but that a series of short years might cause depletion of belowground reserves in the long-term. Contrary to reported positive effect of increased snow depth on plant growth, an investigation of *Cassiope tetragona* in the field sites of the present study showed that there was no difference in growth between *Cassiope tetragona* in fence and control sites before snow fences were put up, but a significant reduction in both growth length and number of leaves in the first summer after the start of the treatment (Wdowiak, 2008). Furthermore, Havström et al. (1993) found that *Cassiope tetragona* showed strong positive growth responses to warmer temperatures, especially at High Arctic sites, which implies that this dwarf-shrub would grow better in control sites with warmer soil temperatures in summer time.

A reduction in growth as response to enhanced snow depth could only be confirmed in non-shrub vegetation in *Dryas* meadow. The proportion of non-woody plants compared to total aboveground biomass was lower in *Cassiope* heath, which might explain why no significant reduction in the growth of non-woody plants was observed in this vegetation type. The sampled plants were not separated into growth of present and previous years and therefore a possible effect on the shrubs might not have been detectable, because the overall weight of those plants was the sum of several years growth, including the years before installation of the snow fences. Since factors that determine the end of the growing season are little-known (van Wijk et al., 2003b) there is the possibility that growing season in sites with enhanced snow depth was delayed, but as long as in control sites and that sampling at a certain date reflected peak growing season biomass for controls, but not for fence sites. In this case differences in growth would partly be artefacts of malapropos sampling.

Increased root growth was observed in sites with deeper snow cover. Although not significant it is interesting to note that other studies found the same trend (Buckeridge and Grogan, 2008). In sites with deeper snow cover, microbial activity in winter is increased and greater decomposition leads to an increase in the nitrogen pool (Brooks et al., 1997; Nobrega and Grogan, 2007; Schimel et al., 2004). Nitrate is influencing root growth (Farrar et al., 2003) and studies where N and P were added to an arctic ecosystem have revealed that root biomass and root length increased in fertilized plots (van Wijk et al., 2003a). A greater amount of respiring belowground biomass might also affect respiration rate. In addition, roots are influencing the rhizosphere microbial community through the C flux from the roots to the soil (Farrar et al., 2003). This flux is a function of root growth and limits the growth of rhizosphere organisms (ibid.). Differences in the amount of root biomass might therefore partly explain the absence of differences in respiration rate between the treatments in summer time.

A delayed start of the growing season, as well as alterations of the soil temperature and moisture regime, could be noticed in sites with increased snow accumulation. Changes in soil moisture and soil temperature regime due to increased snow cover have been shown to cause changes in plant community structure over a 11-years study period (Scott and Rouse, 1995). Walker et al. (1999) suggested that changes in environmental variables as results of variation in snow cover will lead to shifts in plant communities in the long-term and will probably also affect soil chemistry, nutrient availability and even influence permafrost. Most likely, these modifications will profoundly influence the cycling of C in arctic ecosystems. The present study only assessed short-term responses of ecosystems that probably are not yet adapted to changed environmental conditions. Still, results demonstrate that changes in snow cover can affect ecosystem respiration and plant growth. However, long-term studies are needed to thoroughly evaluate how arctic ecosystems might adapt to and feed back on a changed climate.

5.7 Estimating an annual C budget

This study focused on ecosystem respiration and no estimates for C uptake were obtained. Therefore the annual C budget for the studied region can only be roughly estimated from gross C uptake rates reported in earlier studies. Sjögersten et al. (2006) measured gross photosynthetic uptake at growing season in two subsequent years in mesic sites, comparable to the *Dryas* meadow, in some kilometers distance to the sites of this study. If losses through methane emissions and dissolved organic matter are considered to be negligible (Trumbore, 2006) and if furthermore the present studies summer season is extended to include the months June, July and August, then, assuming that uptake rates were at mean growing season level reported by Sjögersten et al. (2006) (0.93 g C m^{-2} d^{-1}), the gross C uptake would have been of a magnitude of 85.6 g C m^{-2}. This value should be ranked as rough overestimation in the light of the assumed length of the growing season, but is still useful to relate the estimated annual respiration rates to a possible uptake rate, indicating that both vegetation types might have been C sources during the study year.

Net ecosystem CO_2 exchange in wet sedge and moist tussock tundra in Northern Alaska during summer time (June-August) studied over a 5-years period varied substantially between the two vegetation types. Wet sedge tundra showed relatively stable uptake rates of 46-70 g C m^{-2}, whereas moist tussock tundra was either in balance or a source of C of up to 61 g C m^{-2} (Kwon et al., 2006). These uptake and release rates during the growing season are in the same order of magnitude as the respiration rates observed during winter time in the present study. Nobrega and Grogan (2007) reported a net growing season carbon uptake of 29-37 g C m^{-2} in birch hummock tundra, a rate about the same range as the observed increase in C loss in *Dryas* meadow in sites with enhanced snow depth. These numbers illustrate the relevance of winter respiration and its possible increase as response to enhanced snow depth for the annual C balance of arctic ecosystems. Alterations of winter respiration may be sufficient to change an ecosystem from being a C sink to become a C source or to increase the C source strength.

On the other hand there are studies indicating that even though winter respiration was increased in sites with enhanced snow accumulation, the net CO_2 efflux during summer was reduced and the annual amount of CO_2 lost from the ecosystem decreased with about 17-56 % in moist and dry tussock tundra (Jones et al., 1998; Welker et al., 2000). This decrease in CO_2 efflux was attributed to enhanced C assimilation in sites with increased snow depth despite a shortened growing season, whereas respiration rates remained on same levels as in control sites (Jones et al., 1998). Contrary, van Wijk et al. (2003b) indicated that annual gross primary production in Alaskan tussock heath decreased with 4 g C m^{-2} for each day that the growing season was delayed. Similarly, it has been stated that net ecosystem C uptake in an arctic ecosystem in Greenland was enhanced by 0.16 g C m^{-2} per day above 5 ºC that the growing season was prolonged with (Grøndahl et al., 2007). In addition the present study has indicated interannual variation in respiration during the growing season. Also differences in net CO_2 flux of arctic ecosystems have been stated to be large from year to year (Welker et al., 2000)

These differences highlight the spatial and temporal variability in the response of arctic ecosystems to changes in environmental conditions. As shown by Havström et al. (1993) even individual plants vary in their response to changes in temperature and nutrient level depending on which part of the species geographical range they come from. Therefore results from investigations at different arctic sites might not be conferrable. In order to elucidate the effects of increased precipitation on the annual C budget of the studied region, further investigations should focus not only on annual efflux rates but also on CO_2 uptake during the growing season. Furthermore, multiyear studies are needed to gain a deeper understanding of the variation in annual C budgets. Since the cycling of C is intimately connected with the cycling of N, it is necessary to study the effect of increased snow depth also on N mineralization.

5.8 Conclusion

The present study has shown that ecosystem respiration exhibits large seasonality with highest rates in summer and lowest rates in winter time. Soil temperature had a strong influence on respiration rate year-round, whereas vegetation type was a primary control in summer but not in winter time.

Since the contribution of winter CO_2 efflux to annual CO_2 efflux was high, changes in winter respiration rate have the potential to affect the C budget of the studied ecosystems. A moderately increased snow cover led to increased soil temperature and enhanced respiration during the cold season, but did not affect summer respiration rate, thus resulting in an overall increase in annual respiration. It is uncertain whether photosynthetic uptake and productivity in sites with enhanced snow depth were affected. However, increased snow depth led to a delayed start of the growing season and had a negative effect on the growth of non-woody plants.

In order to be able to assess possible responses and feedbacks of arctic ecosystems to changes in winter precipitation, future investigations should consider a variety of factors that influence C cycling. Long-term effects of changes in climatic variables will be determined by the way soil organisms as well as plant productivity and community dynamics are affected and by the timescale on which these ecosystem components respond. As pointed out by Oechel and Vourlitis (1994) changes in composition and function of arctic ecosystems might lead to increased CO_2 release in the short-term, but may over the long-term increase C accumulation, thus promoting the sink activity of arctic ecosystems.

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Appendix A Experimental setup

A.1 Detailed description of the study sites

Collars were installed in the same pattern in fence and control sites. Collars in sites with 6 replicates (Table 17) were placed in two rows of three with a mean distance of 3.9 m between the rows and a mean distance of 3.2 m between collars in one row (Table 18, Figure 15). Collars at sites with two replicates (Table 17) were placed with a mean distance of 3.8 m from each other (Table 18, Figure 15). The mean distance of collars from a fence was 7.5 m.

Table 17 Study sites with codes used in Figure 15 and height/length of installed fences as well as numbers of collars in each Fence and Control.

Vegetation type	Site	Fence&Control	Height/Length of each fence (in m)	Number of collars in each Fence&Control
Cassiope heath	A	A1&CA1	1.5/6.7	6&6
		A2&CA2	1.5/6.5	6&6
		A3&CA3	1.5/6.5	2&2
Cassiope heath	B	B4&CB4	1.5/6.3	2&2
		B5&CB5	1.4/5.6	2&2
		B6&CB6	1.5/6.1	2&2
Dryas meadow	C	C7&CC7	1.6/6.5	2&2
		C8&CC8	1.6/5.2	2&2
		C9&CC9	1.6/6	2&2
Dryas meadow	D	D10&CD10	1.6/5.7	6&6
		D11&CD11	1.6/7.2	6&6
		D12&CD12	1.6/6	2&2

Table 18 Distance of collars installed at fence sites from the particular fence.

Fence	Collar at Fence site	Distance from Fence (m)
A1	A1-1	2.9
	A1-2	5.2
	A1-3	7.8
	A1-4	3.6
	A1-5	5.8
	A1-6	7.8
A2	A2-1	4.5
	A2-2	9.5
A3	A3-1	5
	A3-2	7.1
	A3-3	10
	A3-4	5.7
	A3-5	8
	A3-6	10.3
B4	B4-1	8.5
	B4-2	10.9
B5	B5-1	8.8
	B5-2	8.6
B6	B6-1	7.4
	B6-2	7.5
C7	C7-1	9.1
	C7-2	13
C8	C8-1	3.8
	C8-2	7.5
C9	C9-1	7.6
	C9-2	12.1
D10	D10-1	3.3
	D10-2	6.6
	D10-3	10.6
	D10-4	3.3
	D10-5	6.5
	D10-6	10.6
D11	D11-1	5
	D11-2	7.2
	D11-3	10
	D11-4	2.9
	D11-5	6.4
	D11-6	10
D12	D12-1	8
	D12-2	10

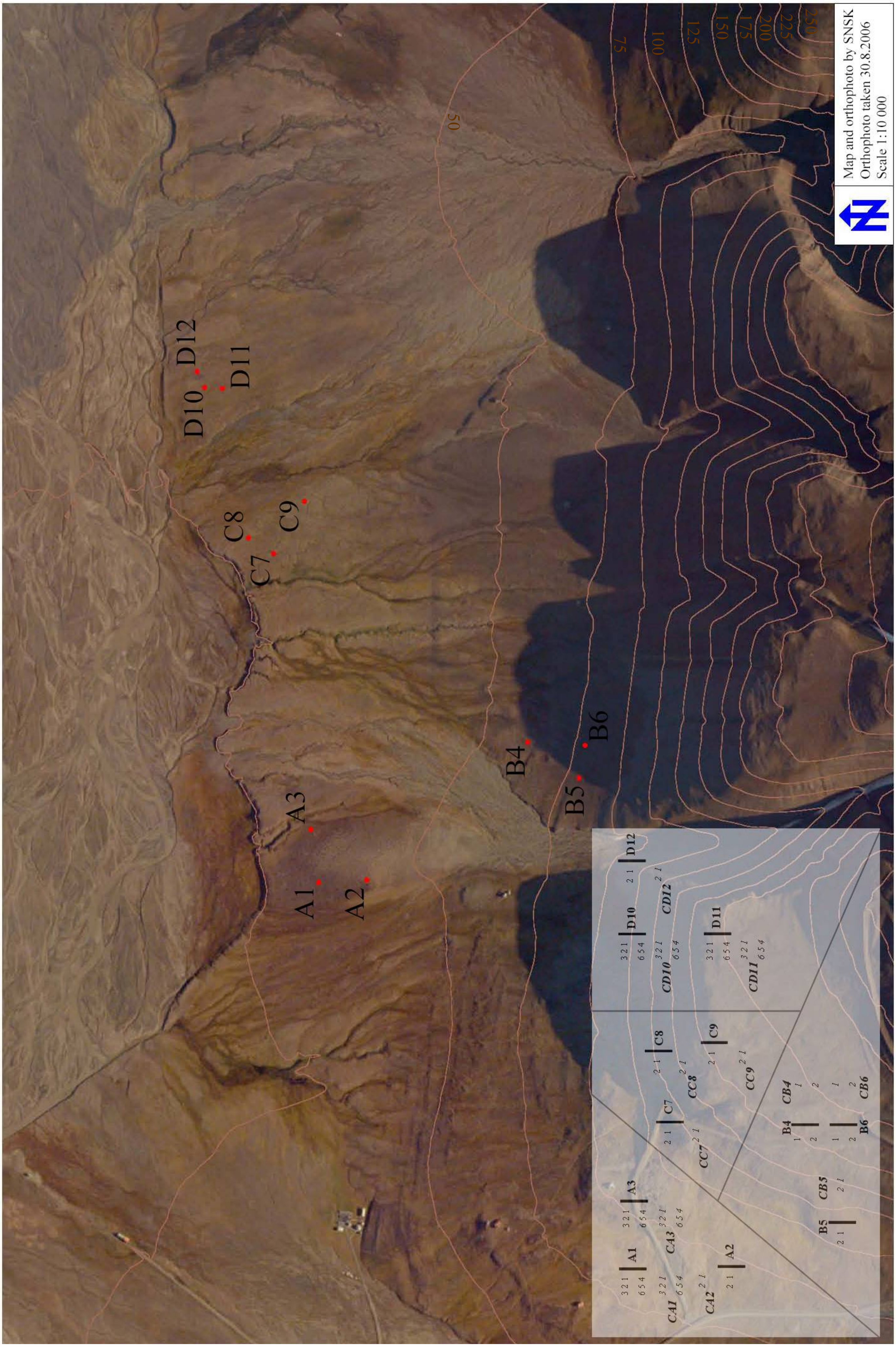

Figure 15. Combined map and orthophoto over the study area (Figure 1). Fences (red points) are marked with codes (Table 17). The overlain white box shows the schematic close-up of the same sites, including controls and a detailed setup. Fences are indicated with black bars. Controls are written in italics. Each number represents one collar in the according site. Equidistance 25 m.

Appendix B Collected data

B.1 Soil temperature

B.1.1 Data loggers

Of 48 installed soil temperature loggers (3.3.1) 12 malfunctioned. Recorded data from the loggers listed in Table 19 were used for further analysis. The distance of each of the functioning loggers from the particular fence is shown in Table 20. Mean distance to a fence was 9.2 m.

Table 19 List over soil temperature loggers used at the different study sites.

Vegetation type	Site	Treatment	Loggers at soil surface	Loggers at 5 cm depth
Cassiope heath	A	Fences	A1, A2	A1, A2
		Controls	CA1, CA2, CA3	CA2, CA3
	B	Fences	B5	B4, B5
		Controls	CB4, CB5	CB4, CB5
Dryas meadow	C	Fences	C7, C9	C7, C8
		Controls	CC7, CC8, CC9	CC7, CC9
	D	Fences	D10, D11, D12	D10, D11, D12
		Controls	CD11, CD12	CD10, CD11, CD12

Table 20 Distance of data loggers from the particular fence.

Vegetation type	Fence	Distance of logger from fence (m)
Cassiope heath	A1	6.5
	A2	9.8
	B4	9.4
	B5	9.8
Dryas meadow	C7	9.2
	C9	10.9
	D10	8.8
	D11	9
	D12	9.2

B.1.2 Selected soil temperature readings

Table 21 Daily minimum and maximum surface soil temperatures recorded per hour in the two different treatments in *Cassiope* heath and *Dryas* meadow in summer 2008. Days when ecosystem respiration was measured are marked with grey.

	Minimum soil temp.ºC		Maximum soil temp. ºC		Minimum soil temp. ºC		Maximum soil temp. ºC	
Treatment	Control	Control	Control	Control	Fence	Fence	Fence	Fence
Date	*Cassiope*	*Dryas*	*Cassiope*	*Dryas*	*Cassiope*	*Dryas*	*Cassiope*	*Dryas*
23/06/2008	1.73	1.05	12.28	11.88	0.53	0.78	6.81	9.63
24/06/2008	5.98	4.46	9.24	9.68	3.00	2.49	5.52	8.68
25/06/2008	4.44	3.65	8.00	7.35	2.48	3.23	5.07	6.82
26/06/2008	3.90	3.04	9.08	10.91	2.16	2.76	7.54	11.82
27/06/2008	4.26	3.37	9.03	7.97	2.90	3.56	8.03	8.83
28/06/2008	2.90	1.99	5.70	6.01	1.87	2.10	5.46	6.25
29/06/2008	2.87	1.70	7.70	9.40	1.75	1.76	6.90	8.48
30/06/2008	2.95	2.16	6.50	5.43	2.32	2.28	6.18	6.05
01/07/2008	2.74	1.86	6.85	6.63	2.17	2.04	6.29	7.27
02/07/2008	4.76	3.73	11.86	11.11	3.69	3.76	11.89	11.26
03/07/2008	4.22	3.52	10.78	13.83	3.18	3.33	10.44	14.68
04/07/2008	7.37	4.76	10.46	10.50	5.91	5.01	9.24	10.27
05/07/2008	6.53	4.93	13.87	15.34	4.98	5.45	12.88	14.61
06/07/2008	5.24	4.37	9.29	7.99	3.61	4.22	8.12	8.57
07/07/2008	5.73	4.75	15.47	18.79	4.19	4.70	13.44	18.84
08/07/2008	6.58	5.86	10.78	10.52	4.98	5.59	9.26	12.19
09/07/2008	5.50	4.49	7.71	6.16	4.08	4.65	6.22	6.65
10/07/2008	4.84	3.63	10.27	9.31	3.28	3.73	9.30	10.26
11/07/2008	3.55	2.57	8.06	6.79	2.10	2.50	6.16	6.63
12/07/2008	3.21	2.25	12.30	11.76	1.84	2.35	10.50	9.61
13/07/2008	4.93	3.84	11.20	12.30	3.73	4.14	10.26	12.24
14/07/2008	5.65	4.49	12.93	10.21	4.53	5.03	12.05	11.99
15/07/2008	6.37	5.33	12.31	15.25	5.00	5.44	12.17	14.60
16/07/2008	8.03	4.94	14.74	11.60	6.76	5.34	12.73	13.42
17/07/2008	6.78	5.75	9.37	8.78	5.57	6.00	8.37	9.05
18/07/2008	6.10	5.21	10.91	11.78	5.03	5.53	10.61	10.78
19/07/2008	5.71	4.76	8.33	7.62	4.57	5.05	7.22	7.74
20/07/2008	5.99	4.97	11.02	10.94	4.87	5.19	10.15	11.41
21/07/2008	6.05	5.01	12.01	12.57	4.89	5.37	11.55	13.24
22/07/2008	7.96	6.91	15.77	17.93	6.78	7.30	15.40	18.02
23/07/2008	7.07	5.65	16.60	18.97	5.70	5.97	17.36	18.55
24/07/2008	7.02	5.86	13.94	14.79	5.85	5.70	12.99	14.92
25/07/2008	7.79	7.39	12.76	12.36	6.84	7.41	11.98	12.75
26/07/2008	7.56	7.21	13.66	12.18	6.67	7.35	14.30	13.30
27/07/2008	6.88	6.46	10.62	12.52	5.97	6.57	10.30	12.79
28/07/2008	6.54	6.17	10.45	10.64	5.57	6.09	9.39	11.54
29/07/2008	5.97	5.42	9.32	7.75	5.54	5.12	9.17	9.55

Table 22 Dates when mean daily soil temperature at 5 cm depth in the two different treatments in *Cassiope* heath and *Dryas* meadow fall below 0 ºC and 5 ºC and rose above 0 ºC and 5 ºC. Dates in brackets indicate days on which soil temperatures stayed in the according interval for at least 7 days. Soil temperatures during winter warming event are not included.

	Cassiope heath		*Dryas* meadow	
Soil temperature	Control	Fence	Control	Fence
at 5cm depth	Date	Date	Date	Date
<5 °C	23.7.(17.8.) 2007	14.7.(7.8.) 2007	19.7.(17.8.) 2007	19.7.(17.8.) 2007
<0 °C	13.9.(6.10.)	1.9.(24.9.)	14.9.(23.9.)	3.9.(23.9.)
>0 °C	7.6.(7.6.)	22.6.(22.6.)	8.6.(8.6.)	23.6.(23.6.)
>5 °C	4.7.(20.7.) 2008	22.7.(22.7.) 2008	8.7.(22.7.) 2008	14.7.(21.7.) 2008

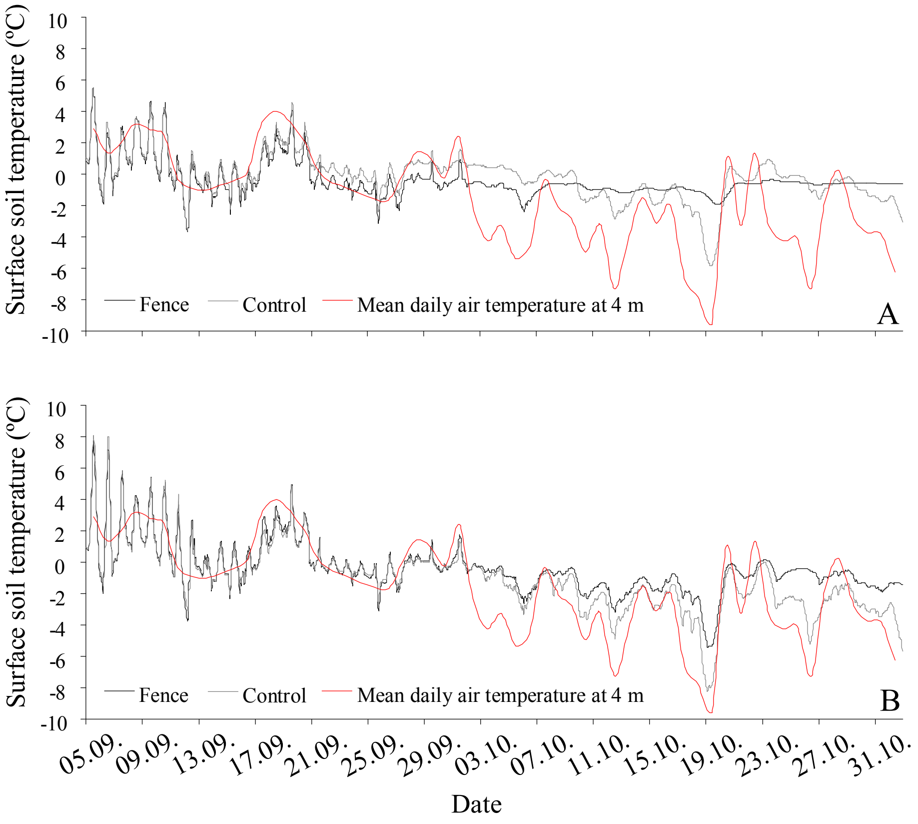

Figure 16. Hourly recorded surface soil temperatures in control and fence sites in *Cassiope* heath (A) and *Dryas* meadow (B) as well as mean daily air temperature in the period 5th September 2007-31st October 2007. Note the diverging soil temperatures between the treatments and the disappearance of diurnal fluctuations after snow was recorded in the study sites in beginning of October.

B.2 Snow distribution

Table 23 Distribution of snow measured in two rows at 2, 4, 6 and 8 m distance behind the fences 20th May 2008. Snow depth data was obtained by penetration through the snow pack with an avalanche probe. Distance between the two rows was 2 m. Fences marked with * indicate those where a significant ($p<0.05$) decrease in snow depth with distance behind the fence in the interval 2 to 8 m could be observed. Fences marked with $^{\times}$ indicate fences where a significant ($p<0.05$) increase in snow depth could be observed in the same interval. Numbers in brackets are F-values and p-values obtained from One-way ANOVA.

Fence	Distance behind fence (m)	Snow depth (cm) row 1	Snow depth (cm) row 2
A1	2	139	136
	4	105	149
	6	124	133
	8	120	118
A2	2	138	149
	4	148	150
	6	156	147
	8	143	137
A3*(F=54, $p<0.01$)	2	146	136
	4	140	134
	6	120	118
	8	111	107
B4$^{\times}$ (F= 14.589, $p<0.01$)	2	124	103
	4	156	150
	6	168	152
	8	168	162
B5	2	116	114
	4	116	120
	6	104	130
	8	86	100
B6* (F=12.321, $p< 0.05$)	2	135	126
	4	130	126
	6	113	125
	8	110	118
C7	2	147	127
	4	152	152
	6	167	160
	8	163	148
C8$^{\times}$ (F=22.888, $p<0.005$)	2	75	69
	4	92	97
	6	126	121
	8	110	126
C9	2	120	111
	4	136	131
	6	138	151
	8	126	128
D10* (F=24.259, $p<0.005$)	2	146	159
	4	145	151
	6	129	135
	8	115	130
D11	2	147	147
	4	147	151
	6	101	142
	8	128	130
D12	2	123	106
	4	92	133
	6	108	82
	8	135	113

B.3 CO_2 efflux and soil temperature

Table 24 Mean measured CO_2 efflux and standard deviation (SD) for the different vegetation types and treatments for each day of efflux measurements during this study (excluding measurements after ice-layer break through (4.3.4)). For detailed description of which fences and controls were measured in each vegetation type see D.3 For numbers of replicates see Table 25).

	Cassiope heath				*Dryas* meadow			
Treatment	Control		Fence		Control		Fence	
Date	**Mean efflux $\mu mol\ m^{-2}\ s^{-1}$**	*SD*	**Mean efflux $\mu mol\ m^{-2}\ s^{-1}$**	*SD*	**Mean efflux $\mu mol\ m^{-2}\ s^{-1}$**	*SD*	Mean efflux $\mu mol\ m^{-2}\ s^{-1}$	*SD*
10/07/2007	**1.09**	*0.36*	**1.25**	*0.63*	**2.04**	*0.54*	**1.80**	*0.67*
11/07/2007	**1.50**	*0.63*	**1.41**	*0.41*	**2.37**	*0.73*	**1.84**	*0.52*
22/08/2007	**0.57**	*0.23*	**0.62**	*0.26*	**1.06**	*0.63*	**0.95**	*0.43*
28/08/2007	**0.69**	*0.38*	**0.69**	*0.48*	**0.62**	*0.44*	**0.84**	*0.35*
04/09/2007	**0.70**	*0.55*	**0.76**	*0.27*	**0.85**	*0.41*	**0.73**	*0.25*
10/09/2007	**0.69**	*0.34*	**0.72**	*0.21*	**0.60**	*0.18*	**0.81**	*0.18*
19/09/2007	**0.75**	*0.18*	**0.78**	*0.17*	**0.81**	*0.15*	**0.94**	*0.18*
26/09/2007	**0.37**	*0.05*	**0.39**	*0.11*	**0.49**	*0.17*	**0.50**	*0.12*
03/10/2007	**0.41**	*0.18*	**0.51**	*0.32*	**0.81**	*0.40*	**0.49**	*0.23*
10/10/2007	**0.26**	*0.14*	**0.22**	*0.18*				
18/10/2007					**0.20**	*0.15*	**0.40**	*0.50*
25/10/2007	**0.31**	*0.22*	**0.39**	*0.22*				
02/11/2007					**0.32**	*0.09*		
15/11/2007					**0.26**	*0.36*	**0.46**	*0.53*
19/11/2007	**0.16**	*0.16*	**0.13**	*0.11*				
28/11/2007	**0.16**	*0.08*	**0.32**	*0.21*				
06/12/2007					**0.11**	*0.08*	**0.29**	*0.30*
18/01/2008	**0.28**	-	**0.31**	*0.25*				
12/02/2008							**0.23**	*0.18*
26/03/2008					**0.11**	*0.08*	**0.26**	*0.17*
27/03/2008					**0.08**	*0.06*	**0.09**	*0.05*
29/03/2008					**0.05**	*0.03*	**0.16**	*0.15*
01/04/2008					**0.09**	*0.04*	**0.13**	*0.13*
14/05/2008					**0.21**	*0.17*	**0.12**	*0.08*
20/05/2008	**0.11**	*0.09*			**0.09**	*0.09*		
30/05/2008					**0.19**			
04/06/2008	**0.89**	*0.58*			**0.99**	*0.19*		
06/06/2008	**0.59**	*0.31*			**1.11**	*1.14*		
07/06/2008	**1.13**	*0.66*			**1.29**	*0.26*		
09/06/2008	**0.86**	*0.45*			**1.06**	*0.24*		
11/06/2008	**0.44**	*0.20*			**0.67**	*0.66*		
12/06/2008	**0.60**	*0.22*			**0.95**	*0.62*		
15/06/2008	**0.58**	*0.72*			**0.72**	*0.34*		
19/06/2008	**0.41**	*0.25*	**0.67**	*0.44*	**0.74**	*0.17*	**0.82**	*0.41*
26/06/2008	**0.55**	*0.31*	**0.99**	*0.75*	**0.81**	*0.53*	**0.89**	*0.36*
02/07/2008	**0.47**	*0.28*	**0.77**	*0.30*	**1.25**	*0.42*	**1.13**	*0.41*
10/07/2008	**0.40**	*0.26*	**0.52**	*0.34*	**1.03**	*0.60*	**0.78**	*0.36*
15/07/2008	**0.90**	*0.41*	**1.01**	*0.51*	**1.92**	*1.00*	**1.33**	*0.45*
21/07/2008	**0.78**	*0.41*	**0.79**	*0.62*	**1.63**	*1.09*	**1.59**	*1.13*
29/07/2008	**0.76**	*0.65*	**0.79**	*0.48*	**1.22**	*1.14*	**1.27**	*1.54*

Table 25 Mean surface soil temperatures and numbers of replicates (not including measurements after ice-layer break through (4.3.4)) for each day of CO_2 efflux measurements during this study. For detailed description of which fences and controls were measured in each vegetation type see Table 29.

	Cassiope heath		*Dryas* meadow		*Cassiope* heath		*Dryas* meadow	
Treatment	Control	Fence	Control	Fence	Control	Fence	Control	Fence
Date	Surface soil temperature (°C)				Number of replicates for CO_2 efflux measurements			
10.07.2007	11.91	11.00	11.44	12.03	14	14	14	14
11.07.2007	13.25	12.39	12.94	13.58	6	6	6	6
22.08.2007	4.81	3.62	3.56	3.82	20	20	20	20
28.08.2007	3.55	2.31	2.16	2.36	20	19	20	20
04.09.2007	3.86	2.63	2.50	2.72	20	20	20	20
10.09.2007	1.60	1.48	1.76	1.89	20	19	20	20
19.09.2007	2.44	1.96	2.49	2.72	14	14	14	14
26.09.2007	-0.23	-1.06	-0.65	-0.72	14	14	20	20
03.10.2007	0.45	-0.71	-0.82	-0.49	14	14	6	10
10.10.2007	-1.62	-0.85	-3.31	-2.08	14	6		
18.10.2007	-2.98	-1.13	-4.70	-2.83			14	14
25.10.2007	-0.10	-0.52	-2.32	-0.45	14	14		
02.11.2007	-2.99	-0.68	-4.88	-1.49			5	
15.11.2007	-4.14	-1.00	-6.15	-1.90			12	12
19.11.2007	-5.91	-1.23	-8.63	-2.39	6	6		
28.11.2007	-6.60	-1.74	-8.45	-3.21	8	12		
06.12.2007	-7.16	-1.77	-8.59	-3.78			13	14
18.01.2008	-5.80	-0.19	-7.24	-1.50	1	6		
12.02.2008	-6.71	-1.83	-7.67	-2.76				5
26.03.2008	-16.37	-6.09	-22.63	-6.46			4	3
27.03.2008	-16.90	-6.30	-23.04	-6.62			6	6
29.03.2008	-15.43	-6.52	-18.47	-6.96			5	6
01.04.2008	-15.84	-6.59	-20.17	-7.10			5	5
14.05.2008	-5.80	-5.31	-5.08	-5.34			6	6
20.05.2008	-5.06	-4.71	-4.65	-4.62	12		12	
30.05.2008	-0.11	-1.32	0.30	-1.37			1	
04.06.2008	0.66	-0.12	4.45	0.01	13		13	
06.06.2008	1.64	-0.11	4.39	0.02	14		13	
07.06.2008	2.84	-0.10	6.72	0.04	14		14	
09.06.2008	4.39	-0.08	5.26	0.06	14		14	
11.06.2008	4.48	-0.08	4.08	0.08	14		14	
12.06.2008	5.68	-0.06	5.65	0.10	14		14	
15.06.2008	3.68	0.36	2.92	0.59	13		14	
19.06.2008	4.44	0.85	4.07	1.03	14	7	14	6
26.06.2008	7.32	5.44	6.66	7.15	14	14	14	14
02.07.2008	7.40	6.70	6.57	7.05	14	14	14	14
10.07.2008	6.87	5.50	5.55	6.13	14	14	14	14
15.07.2008	9.02	7.87	8.92	9.15	20	19	20	20
21.07.2008	8.97	8.01	8.08	8.69	14	14	14	14
29.07.2008	7.34	6.68	6.73	7.19	14	14	14	14

Appendix C Data processing

C.1 CO_2 efflux measurements

C.1.1 Volume correction

Due to heterogeneities in soil surface and vegetation cover the height of the aboveground part of individual collars installed at the study sites differed. Because the volume that is enclosed by the soil flux chamber when placed on a particular collar (the so called system volume) is an important variable for the calculation of efflux during one respiration measurement, each reading had to be corrected for the volume difference that occurred when the height of a particular collar deviated from 3 cm, the standard collar height for the system volume (Box 1). Volume correction was not applied for readings in the period 10.10.2007-30.5.2008 and 10.10.2007-14.5.2008 for control and fence collars respectively. During this period the chamber was always seated on the ice-layer or the frozen soil before reaching the rim of any collar and thus the system volume did not change.

With an exposed soil area of 71.6 cm^2 and a standard collar height of 3 cm the system volume is 991 cm^3 (LI-COR, 2004). Differences from the system volume (Vol_{sys}) were computed as follows:

The aboveground volume of one collar (Vol_{collar}) was calculated based on the exposed soil area and the average of 10 height readings around the inside of the collar. The difference in volume of installed collar from standard collar (ΔVol) was then calculated as:

$$\Delta Vol = Vol_{collar} - \textit{Volume of collar with height of 3cm}$$

Expressed as difference from system volume (ΔVol_{sys}):

$$\Delta Vol_{sys} = (1/Vol_{sys}) * \Delta Vol$$

The corrected efflux (E_{corr}) is then calculated based on the measured efflux (E_{meas}) and the difference in system volume (ΔVol_{sys}):

$$E_{corr} = E_{meas} + (E_{meas} * \Delta Vol_{sys})$$

Box 1. Volume correction for measured ecosystem effluxes.

C.1.2 Conversion of efflux units

The LI-COR system measures CO_2 efflux in µmol m^{-2} s^{-1}. This unit is easily converted to g C m^{-2} d^{-1} using a conversion factor of 1.0368 (Box 2).

Calculation of a conversion factor for the unit µmol m^{-2} s^{-1} to g C m^{-2} day^{-1}:

Based on:

a) $1\ \mu mol\ CO_2 = 12 * 10^{-6}\ g\ C$ and b) $1\ day = 86400\ s$

it follows:

$$1\ \mu mol\ CO_2\ m^{-2}\ s^{-1} = 12 * 10^{-6} * 86400\ g\ C\ m^{-2}\ day^{-1}$$

$$1\ \mu mol\ CO_2\ m^{-2}\ s^{-1} = \underline{1.0368}\ g\ C\ m^{-2}\ day^{-1}$$

Box 2. Calculation of a conversion factor for the efflux units used in this study.

C.2 Modelling of soil temperatures for summer and early autumn 2007

Linear correlations of soil temperatures at the CALM site in Adventdalen (3.3.1) and the different vegetation types and treatments of this study were established for the period 1st to 25th July 2008 and used to calculate soil temperatures between 1st July 2007 and 4th September 2007 based on the CALM data from this period. Mean daily surface soil temperatures from the CALM site were correlated to mean daily surface soil temperatures for each vegetation type and treatment. R^2 values for all four correlations were >0.9 (Figure 17). For modelling soil temperatures at 5 cm depth for each vegetation type and treatment, temperatures were correlated to the mean daily soil temperatures measured at 10 cm depth at the CALM site. R^2 values for these correlations were 0.95 and 0.7 for controls and fences in *Cassiope* heath and 0.95 and 0.89 for controls and fences in *Dryas* meadow respectively.

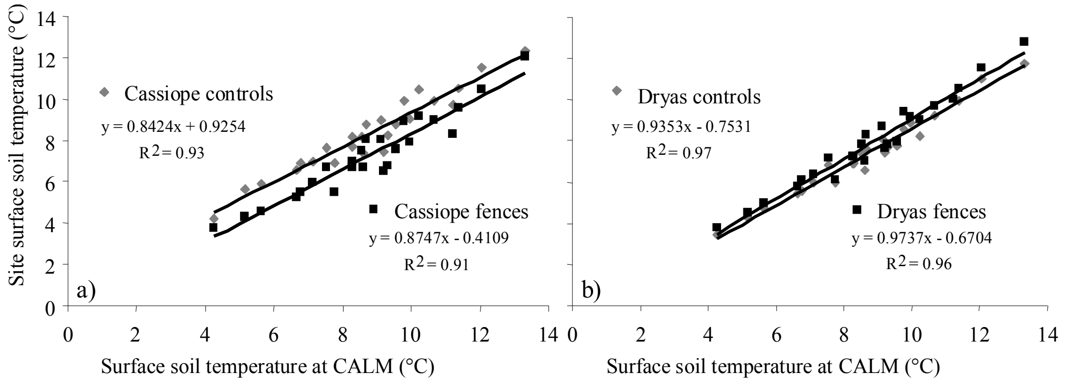

Figure 17. Mean daily surface soil temperatures recorded at the CALM site versus mean daily surface soil temperatures for control and fence sites in *Cassiope* heath (a) and *Dryas* meadow (b) for the time period 1.7.2008-25.7.2008. Linear regression fits are shown as lines. R^2 values for these regressions are 0.93, 0.91 (a) and 0.97, 0.96 (b) respectively.

C.3 Ecosystem respiration models

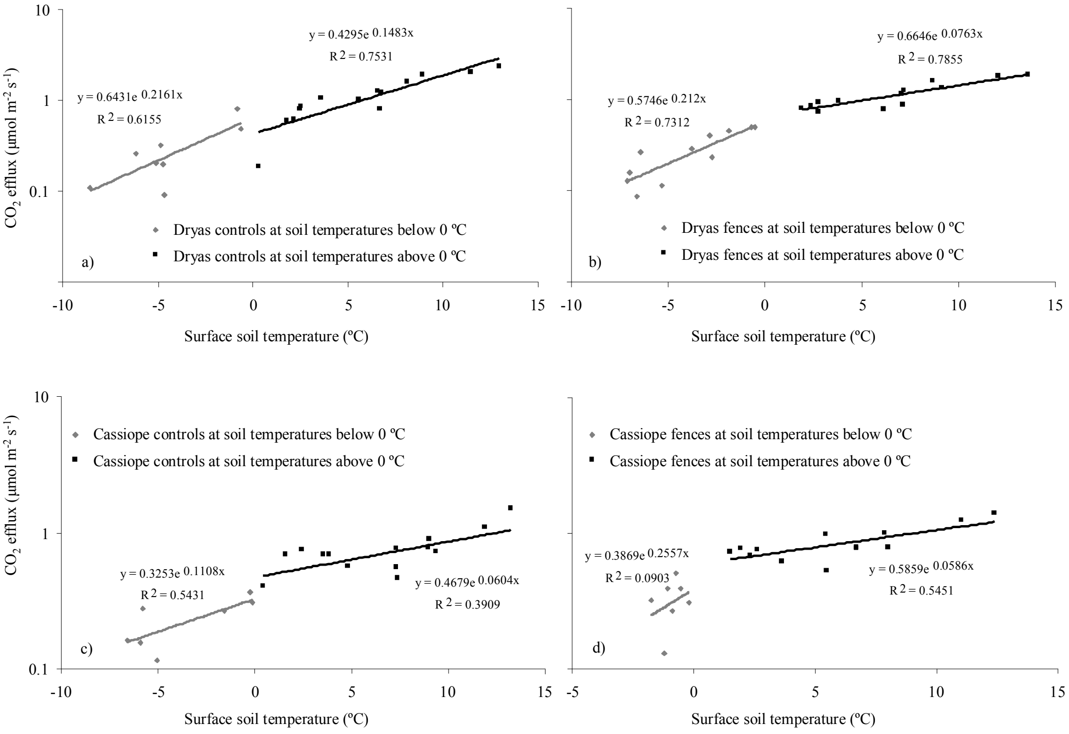

Figure 18. Observed CO_2 efflux versus surface soil temperature (for temperatures above and below 0 °C) in control and fence sites in *Dryas* meadow (a, b) and *Cassiope* heath (c, d). Effluxes measured at end of March 2008 in *Dryas* controls at soil temperatures below -10 °C were excluded. Exponential regression fits are shown as lines. Q_{10} values reported in Table 13 and ecosystem respiration models used in this study (3.5) are based on these regressions. For numbers of replicates behind each data point see Table 25.

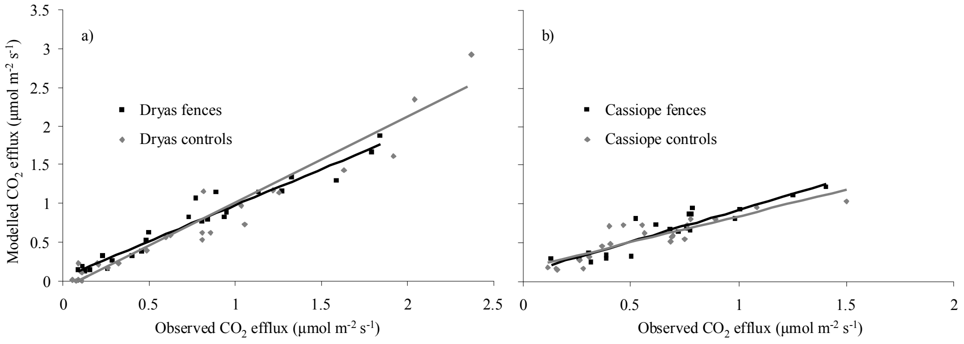

Figure 19. Modelled CO_2 effluxes versus mean observed CO_2 effluxes in control and fence sites in *Dryas* meadow (a) and *Cassiope* heath (b) for the entire study period, excluding spring time values. Linear regression fits are shown as lines. Corresponding R^2 values are 0.94 and 0.93 for fences and controls in Dryas meadow and 0.84 and 0.77 in the according treatments in Cassiope heath. Numbers of replicates per mean efflux value differ (Table 25).

Appendix D Replicates

D.1 Snow depth measurements

Table 26 List over dates and number of replicates for snow depth measurements in the different vegetation types and treatments. Numbers in brackets indicate numbers of snow depth measurements by penetration of the snowpack with an avalanche probe instead of digging.

	Cassiope heath		*Dryas* meadow	
Date	Control	Fence	Control	Fence
03.10.2007	14	14	6	10
10.10.2007	14	5		
18.10.2007			14	14
25.10.2007	14	14		
02.11.2007			5	
15.11.2007			14	13
19.11.2007	12	6		
28.11.2007	15	14		
06.12.2007			14	13
18.01.2008	14	7		
05.02.2008			1	1
12.02.2008			12	5
28.02.2008	1	1		
06.03.2008	3(2)	4(3)		
07.03.2008			3(2)	4(3)
26.03.2008			6	6
01.04.2008			3(2)	4(1)
02.04.2008	3(2)	4(3)		
06.05.2008			4(4)	4(4)
14.05.2008			6	6
20.05.2008	15(2)	48(48)	17(4)	48(48)
30.05.2008	13		11	
04.06.2008	3		1	

D.2 Ice layer measurements

Table 27 Numbers of observations of ice layer thickness in *Cassiope* heath and *Dryas* meadow controls in winter 2008.

	Cassiope heath	*Dryas* meadow
Treatment	Control	Control
Date		
18.01.2008	14	-
12.02.2008	-	11
26.03.2008	-	6
14.05.2008	-	6
20.05.2008	13	13
30.05.2008	13	12
04.06.2008	4	1

D.3 Soil moisture and CO_2 efflux measurements

Table 28 Number of soil moisture readings in the two different vegetation types and treatments at dates of measurement.

	Cassiope heath		*Dryas* meadow	
Date	Fence	Control	Fence	Control
10.07.2007	70	70	70	70
11.07.2007	30	30	30	30
22.08.2007	100	100	100	100
28.08.2007	100	100	100	100
04.09.2007	100	100	100	100
10.09.2007	95	100	100	100
19.09.2007	69	70	70	70
03.10.2007	70	70	50	30
06.06.2008	-	9	-	13
07.06.2008	-	12	-	13
09.06.2008	-	13	-	13
11.06.2008	-	14	-	14
12.06.2008	-	-	-	14
15.06.2008	-	-	-	14
19.06.2008	15	70	16	70
26.06.2008	65	70	61	70
02.07.2008	70	70	70	70
10.07.2008	70	70	70	70
15.07.2008	95	100	100	100
21.07.2008	70	70	70	70
29.07.2008	70	70	70	70

Table 29 Number of collars measured at each fence and control (Figure 15) for all CO_2 efflux measurement campaigns. Measurements after ice layer-break through (4.3.4) are not included. Sites in *Cassiope* heath are indicated with bold letters. *Dryas* meadow sites are shown with non-bold letters. Control sites are marked in italics.

Date	**A1**	**A2**	**A3**	**B4**	**B5**	**B6**	***CA1***	***CA2***	***CA3***	***CB4***	***CB5***	***CB6***	C7	C8	C9	D10	D11	D12	*CC7*	*CC8*	*CC9*	*CD10*	*CD11*	*CD12*
10.07.2007	6	2	6				6	2	6							6	6	2				6	6	2
11.07.2007				2	2	2				2	2	2	2	2	2				2	2	2			
22.08.2007	6	2	6	2	2	2	6	2	6	2	2	2	2	2	2	6	6	2	2	2	2	6	6	2
28.08.2007	5	2	6	2	2	2	6	2	6	2	2	2	2	2	2	6	6	2	2	2	2	6	6	2
04.09.2007	6	2	6	2	2	2	6	2	6	2	2	2	2	2	2	6	6	2	2	2	2	6	6	2
10.09.2007	6	2	6	2	1	2	6	2	6	2	2	2	2	2	2	6	6	2	2	2	2	6	6	2
19.09.2007	6	2	6				6	2	6							6	6	2				6	6	2
26.09.2007	6	2	6				6	2	6				2	2	2	6	6	2	2	2	2	6	6	2
03.10.2007	6	2	6				6	2	6							6	4					6		
10.10.2007	3	1	2				6	2	6															
18.10.2007																6	6	2				6	6	2
25.10.2007	6	2	6				6	2	6															
02.11.2007																			2	1	2			
15.11.2007																5	6	1				6	4	2
19.11.2007	6						3		3															
28.11.2007	6	1	5				4		4															
06.12.2007																6	6	2				5	6	2
18.01.2008	2	1	3					1																
12.02.2008																3	2							
26.03.2008																3						4		
27.03.2008																6						6		
29.03.2008																6						5		
01.04.2008																5						5		
14.05.2008																6						6		
20.05.2008							6		6													6	5	1
30.05.2008																							1	
04.06.2008							5	2	6													5	6	2
06.06.2008							6	2	6													5	6	2
07.06.2008							6	2	6													6	6	2
09.06.2008							6	2	6													6	6	2
11.06.2008							6	2	6													6	6	2
12.06.2008							6	2	6													6	6	2
15.06.2008							5	2	6													6	6	2
19.06.2008	2		5				6	2	6							3	2	1				6	6	2
26.06.2008	6	2	6				6	2	6							6	6	2				6	6	2
02.07.2008	6	2	6				6	2	6							6	6	2				6	6	2
10.07.2008	6	2	6				6	2	6							6	6	2				6	6	2
15.07.2008	6	2	6	1	2	2	6	2	6	2	2	2	2	2	2	6	6	2	2	2	2	6	6	2
21.07.2008	6	2	6				6	2	6							6	6	2				6	6	2
29.07.2008	6	2	6				6	2	6							6	6	2				6	6	2