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Carbon dioxide exchange in the High Arctic – examples from terrestrial ecosystems

PhD thesis, 2006

Louise Grøndahl

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Abstract: The thesis provides an analysis of the exchange of CO_2 between the atmosphere and the vegetation communities in the High Arctic at different temporal and spatial scales. Using a time series of data from a dry heath ecosystem in Zackenberg NE Greenland, it was shown that timing of snowmelt and temperature in the growing season strongly control the interannual variability in ecosystem CO_2 uptake rates. The area has during the past years experienced a warming during the summer season, which was shown to increase the uptake of CO_2 by the vegetation. The increasing earlier snowmelt prolonged the length of the growing season, which in combination with high temperatures increased uptake rates. The dry heath ecosystem in general gained carbon during the summer season in the order of magnitude -1.4 gCm^{-2} up to 32 gCm^{-2}. This result is filling out a gap of knowledge on the response of high Arctic ecosystems to increased warming in the region. A cross scale analysis of eddy covariance and chamber data showed a good agreement between the two methods, which lead to an estimate of CO_2 exchange based on NDVI. A timeseries of satellite imagery for the 2004 growing season provided the opportunity to upscale fluxes from the measurements conducted in the valley to a regional level. Including information on temporal and spatial variability in air temperature and radiation, together with NDVI and a vegetation map a regional estimate of the CO_2 exchange during the summer was provided, elaborating the NDVI based estimate on net carbon exchange.

Keywords: Carbon dioxide, High Arctic ecosystems, upscaling, satellite remote sensing

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Preface

The current thesis is submitted to the Faculty of Science, University of Copenhagen for the fulfilment of a PhD degree. During the thesis work I was based at National Environmental Research Institute, Department of Arctic Environment and registered at the COGCI (Copenhagen Global Change Initiative) Ph.D. School. Field work in NE Greenland was feasible through the funding for the project Spectral Calibration of High Arctic Primary Production Estimation (SCHAPPE). The project was financially supported by the Danish Ministry of Environment (Dancea), the Aage V. Jensens Foundation and the Danish Research Council. Without the unique ZERO (Zackenberg Ecological Research Operations) monitoring programmes in Zackenberg, this work would not have been possible. My sincere thanks to the people behind the programmes. The Danish Polar Center is acknowledged for providing excellent logistical support during the field work.

During the years of this thesis work I was lucky to be surrounded by very helpful colleagues at the National Environmental Research Institute (NERI). I would like to express thanks to my colleagues (too many to mention you all) at NERI for answering questions and keeping an open door for me, it has been a pleasure working with you all. Especially I would express thanks to Hans Meltofte for sharing his knowledge achieved from many years in the Arctic. Also David Boertmann and Peter Aastrup are thanked for valuable information on the High Arctic and comments on the work along the way. I would also like to acknowledge my supervisor, Thomas Friborg, Institute of Geography, University of Copenhagen (IGUC) for sharing knowledge on fluxes, reading manuscripts and general discussions on the project and co-supervisor Mikkel P. Tamstorf, NERI for reading manuscripts and discussing various parts of the project.

At the Institute of Geography, University of Copenhagen (IGUC) I have also had some good colleagues. I am indebted to Charlotte Sigsgaard for always being ready to answer questions on what ever I could come to ask for and sharing her office with me during my weekly work-hours at the IGUC. Thanks also goes to the people I have been working with over the past years, especially Henrik Søgaard for introducing me to this exciting area of gas-fluxes many years ago and always having interest in the current work and Birger U. Hansen for kind help along the process. Also the people at the Institute of Terrestrial Ecology Lotte Illeris and Anders Michelsen for interesting discussions on the data. Torben R. Christensen University of Lund for answering questions with great enthusiasm.

Thanks go to my family and friends for their support and help during the work, especially my husband Martin for "taking-care-of-business" while I was working. And finally Josefine and Magnus for constantly reminding me what's important in life and being such happy and harmonic children.

Louise Grøndahl
Copenhagen, June 2006

List of publications included in the thesis

The thesis consists of a synopsis and five scientific papers which present the results of the work conducted during the PhD study on carbon dioxide exchange in a High Arctic ecosystem. The synopsis gives the background of this work.

Paper I: Grøndahl, L, Friborg, T. and Soegaard, H. Temperature and snowmelt controls on the carbon exchange in a high arctic ecosystem. In Press *Theoretical and Applied Climatology*

Paper II: Grøndahl, L. Tamstorf, M., Friborg, T., Soegaard, H., Illeris, L., Hansen B. U., Albert, K., Arndal, M., Pedersen, M.R. and Michelsen, A. Scaling CO_2 fluxes from plot- and field-level to landscape-level in a high arctic ecosystem using a footprint model and satellite images. Submitted *Global Change Biology*

Paper III: Grøndahl, L., Friborg, T., Tamstorf, M., Sigsgaard, C, Hansen, B.U., Illeris, L. and Michelsen, A.. Assessing a regional carbon dioxide budget for the growing season of a High Arctic area. Submitted *Tellus Series B – Chemical and Physical Meteorology* Special Issue

Paper IV: Soegaard, H., Sørensen, L., Rysgaard, S., Grøndahl, L., Elberling, B., Friborg, T. S.E. Larsen and J. Bendtsen (2004). High Arctic Carbon Sink Identification – A System Approach. *IGBP NewsLetter No. 59, p. 11-14*

Paper V: Christensen, T.R., C. E. Tweedie, T. Friborg, M. Johansson, P. M. Crill, J. A. Gamon, L. Groendahl, J. Gudmundsson, Y. Harazono, C. Lloyd, P. J. Martikainen, W.C. Oechel, H. Oskarsson, N. Panikov and P.A. Wookey. Carbon fluxes and their controlling processes in Arctic tundra: Current knowledge and challenges. Submitted *Ecological Applications*

Abstract

This thesis is a study of the CO_2 exchange between a High Arctic tundra site and the atmosphere. The thesis focuses on an analysis of the monitoring data obtained in the Zackenberg research area, NE Greenland. Continuous summer-time Net Ecosystem CO_2 Exchange measurements have been conducted by Zackenberg Ecological Research Operations (ZERO) research program at a dry dwarf shrub heath since 2000. The measurements from the eddy covariance (EC) mast provide a unique series of measurements on CO_2 exchange from a High Arctic locality. This thesis work presents the fluxes from this monitoring.

During the years of monitoring in Zackenberg, the dry ecosystem has been net sequestering CO_2. This is mainly attributed to two abiotic factors; air temperature and timing of snow-melt. The summer-time temperature and the increasingly early snow-melt in the area and a limited increase in air temperature during the growing season increased uptake rates for the ecosystem. A high degree of interannual variability in the carbon gained during the growing season was seen. The interannual variability seems best explained through differences in the length of the growing season and the amount and rate of snow-melt. The annual status of this High Arctic tundra site is however still unknown, due to the lack of measurements from the highly important autumn and winter period.

Additionally measurements were undertaken at five different dominating vegetation types in the area using the chamber technique. Within the different vegetation types a high degree of spatial and temporal variability is seen within the growing season. The variability in flux might partly be related to the difference in vegetation composition in the plots. The CO_2 exchange obtained from the chamber measurements were compared to the EC measurements from a dry site using a footprint model. An overall agreement was found between the two methods, which allows an upscaling attempt. Upscaling were attempted using two approaches. Based on a vegetation map and a simple model the Net Ecosystem Exchange was derived and additionally the flux assignments approach was tried. It was found that the region is a net consumer of CO_2 during the growing season.

Sammenfatning

Gennem tiderne har klimaet i det arktiske område varieret. I det seneste århundrede er der sket en forøget opvarmning i området, hvilket forventes at fortsætte i dette århundrede. Opvarmningen forventes at have effekt på økosystemerne i regionen. Det er derfor afgørende at have kendskab til hvordan økosystemerne reagerer på abiotiske faktorer i det nuværende klima, for at være i stand til at forudsige hvordan ændringer i klimaet fremover vil påvirke området. Udvekslingen af drivhus gassen kuldioxid (CO_2) er en af de faktorer der fremover kan have indflydelse på klimaudviklingen i Arktis, idet disse områder indeholder store mængder kulstof opmagasineret i jorden. Udvekslingen af CO_2 mellem økosystemerne og atmosfæren er kun undersøgt i få arktiske områder og oftest kun som sporadiske målinger foretaget få gange i løbet af sommer sæsonen, hvilket betyder at yderligere undersøgelser er vigtige. I Zackenberg, NØ Grønland er et måleprogram igangsat med det formål at monitere fysiske og biologiske parametres respons på klimaændringerne.

Dette PhD projekt omhandler udvekslingen af CO_2 mellem en høj arktisk tundra i Zackenberg og atmosfæren. Projektet er et resultat af bearbejdningen af eddy covarians (EC) moniterings data fra en tør hede samt af målinger med kamre i fem dominerende vegetations typer i samme område. Projektet fokuserer på at beskrive de abiotiske faktorer der kan forklare den målte CO_2 udveksling i sommer sæsonen på denne høj arktiske lokalitet. På baggrund af undersøgelserne i dette projekt kan det på baggrund af de seneste 7 års EC målinger konkluderes at vækstsæsonen i Zackenberg er blevet forlænget. Som følge heraf samt som følge af de stigende temperaturer i løbet af sommeren, kan dette økosystem siges at have øget optaget af CO_2. Der mangler dog målinger fra efterårs- og vintersæsonen, hvilket er afgørende for om området på årsbasis optager eller afgiver CO_2. Disse dele af året er vist i andre økosystemer at udgøre en substantiel del af det årlige budget og er derfor afgørende for den samlede udveksling i området. En sammenligning af målingerne fra EC og kamrene viste at der var en god overensstemmelse mellem metoderne, hvilket førte til en opskalering af CO_2 målingerne for et mindre område i Zackenberg dalen. Ved at opstille en simpel model der inddrager parametrene indstråling (PAR), vegetationens grønhed (NDVI) og temperatur, kunne modellen til opskalering af målingerne forbedres. Dette førte til et estimat af den regionale CO_2 udveksling. Denne viste at nogle vegetationstyper i begyndelsen af sommeren og mod slutningen af sommeren

netto afgav CO_2, mens andre vegetationstyper gennem hele perioden optog CO_2 fra atmosfæren. For at afdække status for kulstof udveksling i det cirkumpolare arktiske område, blev et studie af de senere års målinger fra hele regionen foretaget. Det viste at der i nogle områder netto optages CO_2 hvorimod andre områder frigiver CO_2 til atmosfæren. Samlet set vurderes det at regionen er i balance, ud fra de målinger der på nuværende tidspunkt er foretaget.

1 Introduction

The atmospheric content of greenhouse gasses has been proposed as the primary factor in the rising global temperature (IPCC, 2001). One of the major greenhouse gasses is CO_2. During the past century the atmospheric CO_2 content has increased and a continuing increase during the next century is predicted. At present the concentration increases by 1.5 ppm/y, which is mainly attributed to the increasing anthropogenic emissions (IPCC, 2001). The surface air temperature has risen during the 20th century by 0.06°C/decade, while in the Arctic region the rise has been approximately 0.09°C/decade (ACIA, 2005).

Simulations with Global Circulation Models (GCM) predict that the warming effect will be amplified in the Arctic region within the next 100 years, due to feedback mechanisms exerted by the variations in thawing of permafrost, changes in snow-depth and -extent and changes in vegetation patterns. Current predictions indicate future increase of the mean annual temperature of 5°C for the Arctic by the end of the 21st century (Stendel *et al.*, 2006). The climatic effects of the increasing warming are expected to be most pronounced in the Arctic (IPCC, 2001). Research conducted in the Arctic region has documented changes in climate, with regional differences in trends. Recent changes have shown both cooling and warming trends in different parts of the Arctic region. During the past few decades average temperatures in the western part of North America and in Siberia have been increasing by approximately 1°C per decade, while temperatures in mid-west Greenland have decreased by the same extent (Callaghan *et al.*, 1999). This illustrates the complex nature of the responses to climate change in the Arctic region. The future responses to global warming might also have regional differences.

The climatic changes will undoubtedly alter the structure and functioning of the Arctic ecosystems. The predicted global warming is likely to alter the snow coverage and permafrost stability. A continuing trend of a warmer climate at high latitudes is expected to lead to a northward migration of the tree-line, and also increase the length of the growing season and this will in turn probably increase the productivity in the Arctic ecosystems (ACIA, 2005).

The feedback mechanisms between the changing climate and the carbon sequestration are complex and more information on carbon exchange particularly on the High

Arctic areas response to climate warming is required (IPCC, 2001; ACIA, 2005). The soils in the Arctic region contain approximately 14% of the total terrestrial carbon (C) (Post *et al.*, 1982). In addition these soils are among some of the most sensitive ecosystems in terms of climatic change (Maxwell, 1992), which emphasises their importance in future climatic warming. Changes in the C-balance in the Arctic following climatic changes may be of global importance as they may give rise to feedbacks affecting the CO_2 concentrations in the atmosphere and in turn affect the climate systems. Given the potential sensitivity of Arctic tundra to climate change and the expectation that the Arctic will experience appreciable warming over the next century, it is important to assess whether responses of ecosystem function and structure are likely to contribute or mitigate warming of the region.

During the past decades, numerous experiments have been performed in the Arctic tundra, investigating the processes controlling the CO_2 exchange in the region. The majority of studies have been carried out during the growing season, when the photosynthetic uptake of CO_2 exceeds the respiratory loss. There is a general lack of information concerning the fluxes during the winter-time, which constitutes a large proportion of the year. The net annual exchange is largely unknown.

Most of the research on CO_2 exchange in the Arctic ecosystems has been performed in the Low Arctic region e.g. (Oechel *et al.*, 1995; Vourlitis *et al.*, 2000; Harazono *et al.*, 2003). In addition most of the research has been carried out in wet ecosystems, as these are considered to be the most dynamic with respect to CO_2 exchange. Only few studies have been conducted in the High Arctic region (Christensen *et al.*, 2000; Lloyd, 2001a; Rennermalm *et al.*, 2005). The High Arctic area covers $3.2*10^6 km^2$ (Bliss & Matveyeva, 1992). The dry ecosystems cover approximately 58% of the region and contain 42% of the regional C-stock (Bliss & Matveyeva, 1992). Due to the extensive coverage and large C-stock the dry ecosystems play an important role in the total C-exchange of the Arctic.

The present study focus on the exchange of CO_2 between the atmosphere and the dominating vegetation types at a High Arctic locality, using both micro-meteorological and chamber techniques. The series of data presented in this work adds to the observations from the scarcely represented High Arctic and will hopefully contribute with knowledge on the environmental factors affecting the fluxes in the region. The work is based on CO_2 flux measurements conducted in a dwarf shrub heath during the years 1997 and 2000-2004. Additionally, flux measurements from five vegetation types were obtained with chambers during the growing season. The measurements from the summer season 2005 have been included in this synopsis, to expand the series of data further.

Objectives

This PhD project evaluates the CO_2 exchange in a High Arctic ecosystem, during the growing season. Using the available data on CO_2 exchange from a High Arctic dry heath ecosystem, the aim is to describe the interannual variability in growing seasonal CO_2 exchange, through a description of the environmental factors affecting the carbon balance (Paper I). Additionally a comparison of different methods of accessing the CO_2 exchange is performed to enable an estimate the regional exchange during the growing season (Paper II). Further, the obtained data from the growing season is used to estimate the regional CO_2 exchange using remote sensing derivable parameters and GIS (Paper III). By an integration of carbon fluxes from different ecosystems in the region a carbon budget for the landscape was estimated (Paper IV). Finally an evaluation of the integrated C budget for the circumpolar north was assessed (Paper V).

2 Background for the thesis work

This chapter gives a background description for the work in this study. The research area and the climate and dominating vegetation types in the area are described. C-cycling in the Arctic ecosystems along with the factors that affect the balance will be introduced. Finally the techniques used for the measurements of the CO_2 exchange are described.

2.1 The Arctic Region

The Arctic region is characterised by a generally harsh climate, which affects all living organisms in the region. Seasonal variability in climatic parameters is large. During the annual cycle the solar radiation shifts from the summer extreme of 24 hours of sun light to the winter time darkness. The annual sum of incoming radiation is, however, low compared to other regions on the Earth, despite the fact that incoming solar radiation around midsummer is large (Maxwell, 1992). The air temperature spans approximately 40 °C at extremes (Serreze & Barry, 2005) and due to the high albedo during the time of snow-coverage, energy losses are large. The vegetation is adapted to the climatic conditions, the plants develop rapidly after the snow has melted and are optimised to the low summer-time air temperatures. Plant growth in the region is restricted to a relatively short growing season which, depending on latitude lasts approximately three months or less.

Based on floristics and mean monthly temperature Bliss & Matveyeva (1992) proposed a sub-division of the Arctic region into three distinct zones; High Arctic, Low Arctic and Subarctic (see Fig 1). The Low Arctic is characterised by tundra vegetation consisting of dwarf shrubs and various forbs. The vegetation in the High Arctic zone is as diverse as the Low Arctic, the density and coverage of the vegetation is however more sparse. The mean temperature for the High Arctic in the warmest months is less than 5°C, whereas the Low Arctic is characterised by temperatures ranging between 5 °C and 10°C. The Subarctic region is a transitional zone in which scattered forest occurs. The temperature in this zone exceeds 10°C in the warmest month.

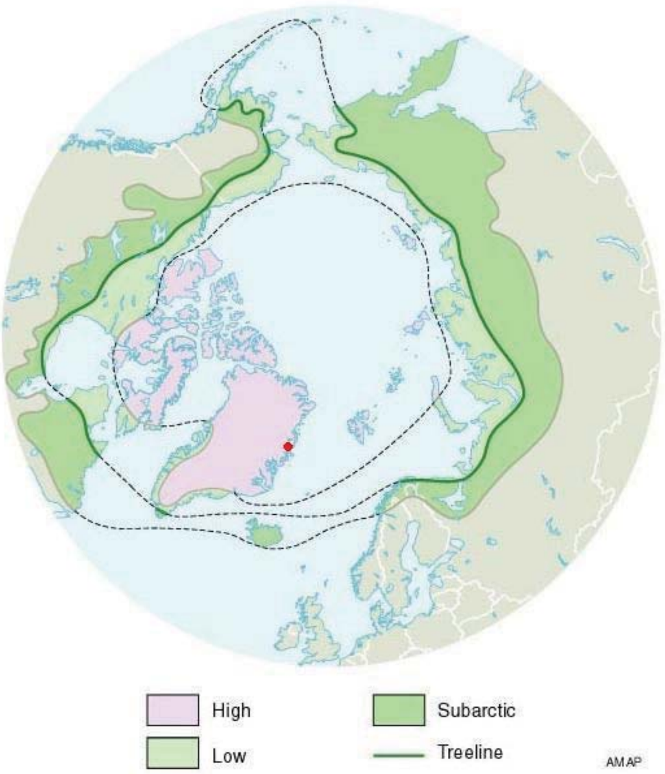

Figure 1. Floristic division of the Arctic region. The red spot indicates the location of the Zackenberg Research Area. Source:AMAP

2.2 Zackenberg Research Area

The Zackenberg Research Area (74°30'N and 21°00'W) is located in the National Park of North and East Greenland. The area is within the High Arctic zone as seen from Figure 1.

The landscape is mountainous with several peaks having altitudes between 1000 and 1400m. Elevation in the valley varies between a few meters above sea level at the coastal part to 100 m.a.s.l. at the inner part. The valley is underlain by permafrost and is characterised by a great diversity in plant communities, from the sparsely vegetated slopes to the more densely vegetated lowlands. The area was chosen in the late 1990s to represent a pristine locality in the High Arctic suitable for monitoring a range of different parameters for an assessment of the climate change scenarios implications in the region. The Zackenberg Ecological Research Operations (ZERO) monitoring programme was initiated in July 1995. Since then monitoring and extensive research has been carried out in Zackenberg valley (Fig 2) during the summer months, from snow-melt until the end of August. An automatic weather station provides a year round continuous data series which comprises approximately 10 years. Although the research area is located in the High Arctic zone, the local climate in the valleys of the region deviates from the strict definition of the High Arctic climate, with average temperature in the warmest month of 5.5°C, which is above the limit for the temperature in a High Arctic area. The annual mean temperature is -10°C. At the nearby Daneborg station a long-term meteorological data series has been recorded since 1958. The station has recorded average temperature in the warmest month (July) of 4.1°C, while the average temperature in the coldest month is -19.8°C (Cappelen *et al.*, 2001). From the timeseries at Daneborg, a slight increase in July mean air temperature is observed, whereas the temperature in the coldest month, January, shows no significant change in mean monthly air temperature (Cappelen *et al.*, 2001). So far, no significant change in annual mean air temperature has been observed in Zackenberg. However, there is a trend which indicates increasing mean air temperature in the warmest month, which is supported by the long-term time series from Daneborg. Average annual precipitation measured in Zackenberg has ranged from 148mm to 263mm, of which 87% falls as snow during the winter time (ZERO, 2005).

During the summer period, between June and August, the region is characterised by 24 hours of solar radiation. The snow coverage in the area is extensive, with snowdepth during winter of approximately 0.7m, which quickly melts in the period from late May to mid June; the surface is usually snow-free from late June. Consequently the plant growth is limited to a relatively short growing season in the order of 2.5 months or less during the summer.

In the Zackenberg area continuous permafrost is found, which is a characteristic feature of the Arctic (Kane *et al.*, 1992). In the summer the active layer depth ranges between 0.5 and 0.6m; recent observations have however shown active layer depth of approximately 0.75m depth (ZERO, 2005). The dominating wind direction for the whole year is N to NNW, but in the summer season the prevailing wind is S to SE. On sunny summer days, sea breezes occur, with day-time wind coming from S to SE, and at night-time wind is from the N. Average wind speeds in the summer are usually below 4 ms^{-1}.

Different methodologies have been used for measurements of CO_2 exchange between the ecosystem and the atmosphere. Since 2000 eddy covariance measurements have been conducted continuously each summer at a dry dwarf shrub heath. Data included in this work is from a previous experiment conducted in 1997 (Soegaard *et al.*, 2000) and the period 2000 to 2004. Additionally, a field experiment was carried out in the 2004 growing season, using the chamber technique.

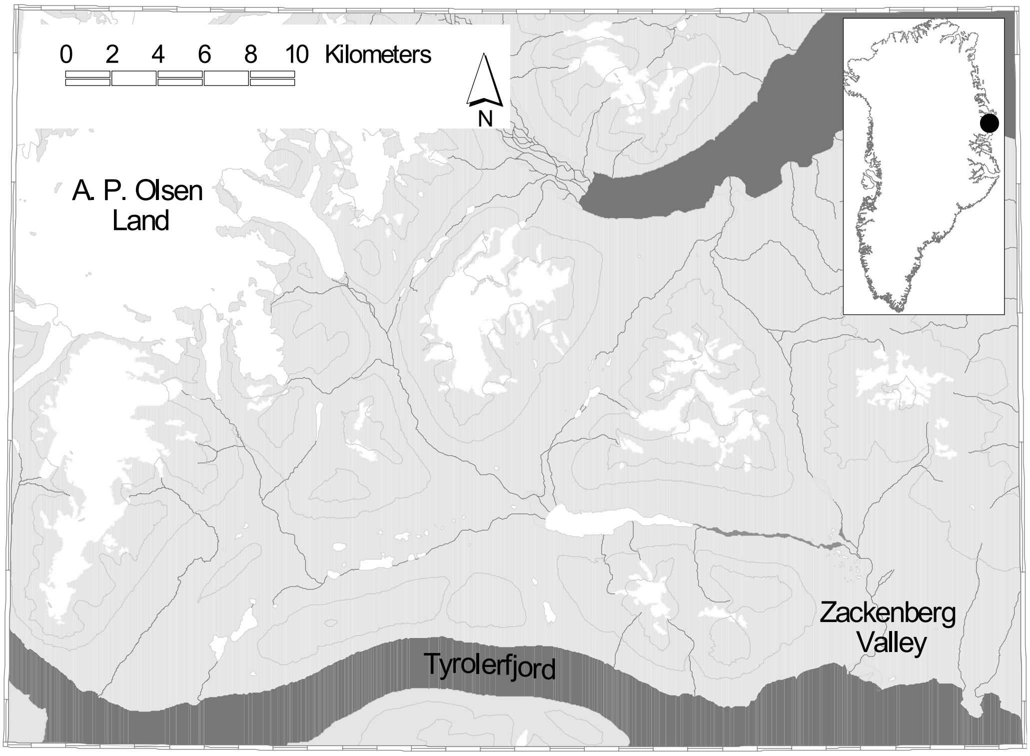

Figure 2. The Zackenberg Research area, the map in the box has a dot marking the location of Zackenberg in Greenland.

2.2.1 Vegetation in the Zackenberg area

As mentioned above the Zackenberg region is extensively vegetated. Mapping of the major plant communities in the area resulted in a classification of plant communities (Bay, 1998). Five dominating vegetation types are identified: fen, grassland, *Cassiope* dwarf shrub heath, *Dryas* dwarf shrub heath and *Salix* snowbed. They are distributed spatially based on topography, hydrological conditions and soil. In total these vegetation types cover 68.5% of the area mapped by Bay (1998) and they are all characteristic of the Arctic tundra (Paper II; III). In the Zackenberg valley *Cassiope* heath occurs in the lowland on moist ground and is dominated by *Cassiope* and a few herbs. The *Dryas* dominated heaths are found both in the lowland but occur more frequently on sloping terrain. Often *Dryas* heath is mixed with graminoids and *Salix arctica*. The *Salix* snowbed vegetation type is found at locations with a prolonged snow cover and is dominated by *Salix arctica* mixed with a few herbs and graminoids. Grassland occur both in the lowland and on the slopes, on moist soils with high organic content. The fens are only found on level terrain with hummocky topography in the lowland, and dominated by sedges and graminoids. This ecosystem is characterised by soils with high content of organic material and is often water logged throughout the growing season. The commonly found species in each of the vegetation types are described in Paper II and Paper III.

2.3 CO_2 exchange in the Arctic

The CO_2 exchange between the terrestrial ecosystem and the atmosphere is the result of two opposing processes; photosynthesis and respiration (Ruimy *et al.*, 1995).

The terrestrial ecosystems assimilate CO_2 through photosynthesis and release CO_2 through respiratory processes. Photosynthetic assimilation or Gross Ecosystem Productivity (GEP) is a light controlled process where CO_2 is a source of carbon and light, i.e. the photosynthetically active wavelengths (PAR) is used as energy. During the summer the photosynthetic uptake of CO_2 exceeds the respiratory carbon losses, the ecosystem is a sink for CO_2.

In general the plant growth in the Arctic is not light limited, the light saturation point is usually close to 400-500 $\mu molm^{-2}s^{-1}$, normally the mid-day PAR values vary from 1500 $\mu molm^{-2}s^{-1}$ to 1800 $\mu molm^{-2}s^{-1}$ on sunny days. However, other factors are also important, such as plant phenology, soil water content and soil and air temperatures (Griffis & Rouse, 2001). The uptake of CO_2 is favoured by high light levels, warm temperature and adequate soil moisture. The quantity and quality of green biomass and the species composition influences the seasonal magnitude of CO_2 uptake.

The terrestrial ecosystems release carbon to the atmosphere through respiratory processes by plants (autotrophic respiration). Fauna and micro-organisms decompose organic matter in the soil and thereby release CO_2 through heterotrophic respiration. The total respiration from the ecosystem (ER) is the sum of the autotrophic (Ra) and heterotrophic (Rh) processes. The rate of Ra is regulated by temperature and the fraction of assimilates allocated to growth, while Rh is controlled largely by the soil temperature and soil moisture (Ruimy *et al.*, 1995). Soil moisture affects the soil microbial activity, which has a tendency to rise shortly after rainfalls (Illeris *et al.*, 2003). The soil respiration is related in an exponential fashion to soil temperature when there is no soil moisture limitation (Lloyd & Taylor, 1994). Respiratory processes has also been shown to occur at subfreezing temperatures (Zimov *et al.*, 1993; Oechel *et al.*, 1997), indicating that carbon can be lost even when the soil is frozen and snow is covering the surface. This emphasises the importance of winter time flux measurements in the Arctic (Paper V).

If the uptake exceeds the loss of CO_2, the photosynthesising process dominates, and the ecosystem is a sink of CO_2. If the opposite occurs, the respiratory process dominates and the ecosystem is a source of CO_2. The Net Ecosystem CO_2 Exchange (NEE) is the balance between the assimilation of CO_2 and the loss through the respiratory processes. The processes can be briefly described as:

Daytime:
NEE = Ra +Rh - GEP =ER - GEP

Night:
NEE = Ra + Rh = ER

The micro-meteorological sign convention is used; consequently ecosystem uptake of CO_2 refers to dominating photosynthesis, *i.e.* negative flux. Release and loss of CO_2 refers to dominating respiration, *i.e.* positive flux.

2.4 Carbon cycling in the Arctic

Due to the climatic conditions the Arctic ecosystems are characterised by low primary productivity and slow turn over rates. Arctic ecosystems, however, tend to accumulate organic matter, C, because decomposition and mineralisation processes are even more strongly limited than productivity by the Arctic environment, particular the cold, wet soil environment. Because of this slow decomposition, the total C-stock has historically been increasing. Research during the past few decades does however reveal a change in this pattern.

The net C-balance of Arctic ecosystems may vary from year to year, resulting in annual loss or gain of carbon to the ecosystem, depending on the environmental conditions. The entire Arctic circumpolar region is very poorly studied with respect to C-exchange. Long–term measurements in the Arctic region are scarce, but necessary to conclude on the ecosystem response to changes in environmental factors. The majority of the studies have been conducted in the wet ecosystems of the Sub and Low Arctic region and during summer season (e.g. Griffis *et al.*, 2000; Aurela *et al.*, 2001). In the past decade also a few areas in the High Arctic have been studied (e.g. Soegaard *et al.*, 2000; Illeris *et al.* 2003, Welker *et al.* 2004; Paper I-IV).

The global warming is expected to have large effects in C-exchange between the biosphere and atmosphere in the Arctic. The present annual balance of CO_2 in the Arctic is however uncertain. Net annual accumulation of carbon (Christensen *et al.*, 1997) as well as net loss of carbon (Oechel *et al.*, 1995; Jones *et al.*, 1998) has been reported. These differences are likely to inherit from the differences in the ecosystems (e.g. soil composition, vegetation coverage/types, soil moisture conditions) in the Arctic region as well as differences in period of study. For instance, some of the estimates are based only on summer time CO_2 fluxes, not taking the losses during the shoulder seasons in spring and autumn into account. In addition losses during the winter time is poorly documented in the Arctic region. This period totally lasts up to 9 months for most Arctic locations and consequently constitutes a large fraction of the year. Winter-time experiments have revealed substantial losses of CO_2 and therefore this is a period of great importance in the annual C-budgets (Zimov *et al.*, 1996; Oechel *et al.*, 1997; Fahnestock *et al.*, 1999) in terms of the ecosystem being a net sink or source.

From recent work conducted in Alaska a change in C-exchange is seen. In the 1960s and 1970s the ecosystems seemed to accumulate C in the wet and moist ecosystems. This pattern was however changed in the 1980s and 1990s, where net losses of C were reported from the same ecosystems (Oechel *et al.*, 1993; Vourlitis & Oechel, 1997; Vourlitis & Oechel, 1999). This shifted again at the end of the 1990s and the ecosystem once again sequestered carbon (Harazono *et al.*, 2003). The shift from sink to source and back to sink again is attributed primarily to changes in temperature which might increase the mineralisation of nutrients, mainly nitrogen. Most of the Arctic ecosystems are considered to be nutrient limited (Nadelhoffer *et al.*, 1992) and increasing temperatures increase the mineralisation of the litter, which then results in increased net primary production.

In the High Arctic region the ecosystems have been shown to gain CO_2 during the growing season (e.g. Soegaard & Nordstroem, 1999; Soegaard *et al.*, 2000; Nordstroem *et al.*, 2001; Welker *et al.*, 2004; Rennermalm *et al.*, 2005; Paper I).

GCM's predict that the Arctic region will be the area of most pronounced warming in the future. It is therefore essential to gain specific knowledge about the inherent temporal variability and long-term development in the ecosystems of the region to evaluate the potential effects of future climate change. A number of factors, abiotic as well as biotic, affect the CO_2 exchange in Arctic ecosystems and therefore changes in these factors will have impact on the future C-balance. The main abiotic factors controlling the C-balance are found in this study to be snow coverage and temperature (Paper I); a few others which are also important will be briefly described here.

The snow coverage in the Arctic is often extensive and the surface is commonly covered by snow between eight and nine months of the year. The occurrence of snow on a specific site changes the surface albedo dramatically and thereby the energy balance of the site. The snow cover insulates and protects the evergreen and winter green species from the low temperatures that creates frost damage on the vegetation. Consequently changes in snow coverage even in this period of year might have great impact on these ecosystems (Hinkler, 2005). The photosynthesis and phenological development of the plants is strongly dependent on snow-free conditions. Change in timing of snow-melt is therefore crucial to the ecosystem. The climate change scenarios predict increased wintertime precipitation, but the higher temperatures might in contrast cause an earlier snow-melt.

Increased temperature during the growing season in the Arctic region has commonly been expected to increase the respiratory rates and consequently cause the ecosystems to loose carbon. But also increased mineralisation rates might be an effect of this, and therefore plant growth might increase in the often nutrient limited Arctic ecosystems (Nadelhoffer *et al.*, 1992). However, decomposition might also increase under increasing temperatures. The photosynthetic rates have especially in the High Arctic region been seen to increase at increasing temperatures, possibly due to the temperature range in photosynthetic activity, with optimum levels ranging from 10-15°C (e.g. Welker *et al.*, 2004) in addition the majority of the vegetation types in this particular region are close to their northern limit (Havstrom *et al.*, 1993) which cause rapid responses to changes in environmental conditions.

Changes in precipitation have been predicted. By the end of the 21st century an increase of 35% is expected for NE Greenland (Stendel *et al.*, 2006). Depending on the time of year the precipitation might either fall as snow or rain. If the snow-fall increases in the area the timing of snow-melt might be affected. During the summer increased precipitation in the area might increase the soil moisture and hence affect the respiratory processes (e.g. Illeris *et al.*, 2003). Along with increased precipitation,

the cloud coverage might also increase in the region, which in turn decreases photosynthetic activity (Joabsson & Christensen, 2001).
Permafrost preserves the carbon stored in the soil. Warmer climatic conditions could alter the permafrost and an increasing active layer depth possibly resulting in a mobilisation of the large amounts of stored carbon in these ecosystems. Such changes might simultaneously have large feedback on the terrestrial C-balance. Therefore areas underlain by permafrost are fragile ecosystems, sensitive to transformation in a changing climate (ACIA, 2005).

2.5 Methods of assessing the CO_2 exchange

Arctic landscapes exhibit a considerable spatial heterogeneity in micro-topography, soil temperature and plant species composition. It is therefore necessary to use different methodologies to measure the spatial and temporal variability of the fluxes. Generally, measurements of CO_2 fluxes in Arctic landscapes have involved the use of both micro-meteorological and chamber techniques. The two techniques operate at different scales. The micro-meteorological towers are used for characterising fluxes at the field level (areas up to hectare scale), while the closed gas-exchange systems (chambers) provide estimates at plot-level from a well defined surface of less than $1m^2$. This provides detailed information from a specific composition of plants within the area.

By far the chamber and cuvette techniques have been the dominant methods for measuring CO_2 exchange in the Arctic. However, the micro-meteorological approaches are becoming more frequently applied. Depending on the purpose of the study these two methods might be used. The chamber technique is considered to be the method of choice for process-level studies of soil and microbiological factors controlling gas fluxes and have been applied for detailed studies on the response to different kinds of manipulations, e.g. fertiliser addition and increased precipitation. The micro-meteorological approaches yields information on the total flux, i.e. from both soil and vegetation, to or from the ecosystem and are frequently used for studies on ecosystem balances. It is considered the most direct way to determine canopy and surface fluxes (Baldocchi, 2003). The eddy covariance technique is one of the commonly used micro-meteorological methods for providing the net ecosystem exchange of CO_2.

Although there are many advantages using either of the two techniques, there are also disadvantages which need to be considered when measuring CO_2 fluxes.

The major disadvantages using the chamber method is the disturbance to the ecosystem within the chamber. Chambers have been described to influence the soil and plant environment directly, which causes limitations to the method. Reliable result may not be achieved when temperature, radiation, energy balance and gas concentration inside the chamber differ from the ambient conditions. In addition the turbulence inside the chamber might differ from the outside, which might create boundary layer conditions or flushing of gas from the soil (Hooper *et al.*, 2002). Moreover, the chamber method suffers from limitations associated with the lower temporal and spatial sampling and by being intrusive (Waddington & Roulet, 1996).

The micro-meteorological method requires sufficient turbulent mixing in order to separate the fluxes into sub-footprint spatial components. This is the area of the canopy-atmosphere surface upwind of the sensor, for which the measurements are valid. The footprint is transient compared to the chamber technique, and highly reliant upon the wind speed and boundary layer conditions during the period of measurements. Furthermore, the conservation principle applies; inputs and outputs must balance (Baldocchi, 2003). Therefore, there cannot be any advection, convergence or divergence of the measured fluxes. To fulfil these demands, the instrument, measuring surface fluxes, has to be mounted within the surface boundary layer. Especially during night-time, turbulence might be dampened and consequently the exchange between the ecosystem and the atmosphere is not measured correctly.

The closed chamber and the eddy covariance techniques were applied to measure the net ecosystem CO_2 exchange in Zackenberg (Paper I; II; III).

Closed chambers were applied for measuring fluxes in five different vegetation types (Paper II; III). Aluminium collars with a footprint of $0.04m^2$ were inserted permanently into the soil at five vegetation types, prior to the field campaign, allowing the ecosystem to adjust to the experimental conditions. When performing the measurement a transparent plexiglas chamber was placed on the collar fitted with a water channel to ensure air tightness from the ambient atmosphere. A fan ensured thorough mixing of the air in the chamber. The changes in CO_2 concentration during a timespan of 3 minute and 20 seconds was measured and recorded with an infrared gas analyser. Simultaneous measurements of PAR and relative humidity in the chamber were performed. Due to the heterogeneity in abiotic factors and the patchiness of vegetation distribution within the vegetation types, three replicates were used to describe the flux of the individual vegetation types. This reduced the spatial variability in the flux measurements. The method is very labour intensive if extensive temporal sampling is needed. Therefore, measurements presented in Paper II and Paper III are daytime results.

The ZERO monitoring programs provide growing season measurements of CO_2 exchange from a dry dwarf shrub heath. A three-dimensional sonic anemometer, measuring the wind speed and wind direction and a closed path infra red gas analyser (IRGA) was used. The sampling tube inlet to the IRGA was mounted on a tower, 3m above the surface (Paper I). Fluxes were logged at 21 Hz by using the EdiSol software package (Moncrieff *et al.*, 1997). Half-hourly CO_2, momentum, water vapour, and sensible heat flux data were computed. An adequate fetch was ensured by placing the mast at the heath extending approximately 800 by 1200m. To interpret the fluxes derived from the heterogeneous vegetation mosaics additional information is required about the flux footprint. The footprint of the mast was derived using a footprint model (Paper II), and originated from an area extending approximately 200-500m from the mast, depending on the stability.

Gaining a better understanding of the responses of C-cycling to climate change requires study of the ecosystem at a variety of scales. The two mentioned techniques apply to different spatial and temporal scales; they do however complement one another and contribute to a better understanding of the response of the ecosystem. Analyses of eddy covariance and chamber fluxes allow the gas exchange processes of different vegetation types (ecosystems) to be described, quantified and compared over space and time. Under ideal conditions (i.e. homogeneous fetch and level and homogeneous terrain) the chamber and eddy covariance method would yield comparable measurements. It is important to make sure that the results from the two methods are comparable, especially when upscaling measurements from plot- or field-level to landscape or regional level (Paper II). Consequently, intercomparison is needed in order to make sure that the two methods actually provide comparable information (Paper II). In previous studies the two methods have been found to have similar CO_2 fluxes (Norman *et al.*, 1997; Oechel *et al.*, 1998; Zamolodchikov *et al.*, 2003).

2.6 Application of remote sensing for estimating regional budgets

Accessibility to the Arctic region can be difficult. Obtaining a regional budget for the region or just parts of the region based on field measurements, can be difficult due to logistical constraints. Applying remote sensing tools is therefore very useful, due to the large spatial coverage provided by the satellite imagery, enabling large regions to be monitored. The spatial resolution of images acquired from the newer sensors (e.g. Aster) provide reasonable spatial resolution; the temporal resolution however might be a problem, due to the frequent cloud coverage in the Arctic.

Beside the spatial coverage, satellite imagery provides a unique option to monitor changes in vegetation density and greenness. Consequently optical remote sensing has been used to document the distribution and spatial arrangement of Arctic terrestrial vegetation (Stow *et al.*, 2004).

Vegetation indices are commonly inferred products from satellite imagery. They are based on the reflectance from the leaves observed in the two bands; red and near-infrared. The radiation scattered and reflected from the plant canopy has a characteristic spectrum in the visible and short-wave infrared part of the electromagnetic spectrum. This reflectance pattern is distinguishable from that reflected by the surroundings of the canopy. The visible radiation (400-700 nm) is absorbed by the plant pigments for photosynthetic purposes, with peak absorption in the blue (450 nm) and the red (600-700 nm). A sharp increase in reflectance is seen for wavelengths greater than 700 nm. The red reflectance tends to decrease with the amount of green vegetation due to the absorption by chlorophyll, whereas near-infrared (NIR) reflectance (700-1000 nm) tends to increase because of light scattering by the plants mesophyll cell tissue (Jensen, 1996). The differences in reflectance pattern in the two distinguishable bands are used for an index describing the greenness of the vegetation. This is often used as a surrogate for the phenological development during the growing season, and consequently the photosynthetic activity of the vegetation has been inferred from satellite imagery. The most commonly used vegetation index is the Normalised Difference Vegetation Index (NDVI). Remote sensing has been increasingly applied in Arctic C-cycle studies through empirical and process-oriented remote sensing algorithms linking spectral information such as the NDVI to more detailed ecosystem processes such as net primary production (Hope *et al.*, 2003; Markon *et al.*, 2005) and net CO_2 flux (Whiting *et al.*, 1992; McMichael *et al.*, 1999; Oechel *et al.*, 2000). Linear regression based on spectral reflectances from the vegetation has been used for scaling of the net ecosystem CO_2 exchange (e.g. Whiting, 1994; McMichael *et al.*, 1999; Paper II). Based on a temporal series of images from the NOAA-AVHRR satellite have documented a general increase in plant growth and increasing growing season length for the circum polar Arctic (Myneni *et al.*, 1997). This documents the applicability of remotely sensed data in a climate change perspective.

Different empirical approaches have been assessed when upscaling locally obtained fluxes to a regional level. Roulet *et al.* (1994) used the area weighting method which assigns a flux from a given ecosystem type to the area covered by the ecosystem type. This method was also applied in Siberia (Heikkinen *et al.*, 2004) for a regional estimate. However, compared to this simple approach additional parameters, besides the LAI or the surrogate NDVI, could be used. A photosynthetic dependency on PAR and temperature has been used for estimating GEP. Respiration is as mentioned previously also dependent on temperature. Oechel *et al.* (2000) derived a simple model based on a few meteorological and satellite derivable parameters; air temperature and, PAR and NDVI, to estimate NEE on a regional scale using satellite imagery. Although using images with a coarse spatial resolution, they gained convincing results (Vourlitis *et al.*, 2003), and it is a suitable approach for upscaling fluxes measured at plot- and field scale, when detailed studies on the vegetation type responses and soil properties are not present.

3 Results and discussion

The diversity in reported CO_2 fluxes from the Arctic region within the past few decades call upon a thorough investigation of the fluxes from the region. Studies have reported net losses of CO_2 from some areas in the Arctic whereas other areas seem to have net uptake of CO_2 (Paper V)

The monitoring program in Zackenberg provides a time series of CO_2 data obtained with the eddy covariance technique at a dwarf shrub heath ecosystem. In this study these data have been used in addition to chamber measurements from five vegetation types in the Zackenberg area to document the recent status in CO_2 exchange in the High Arctic and especially adding to the scarcity of data from the region (Papers I,II, III, IV and V). In the following the results are summarised and discussed.

3.1 Seasonality in Net Ecosystem Exchange in the Arctic

The seasonal cycle of the CO_2 exchange in the Arctic is distinctly divisible into the growing season and the non-growing season. This division is determined by the ability of the ecosystem to utilise the solar energy, therefore the surface has to be free of snow before the growing season can start. Abiotic as well as biotic factors determine the length of the growing and non-growing seasons, following the seasonal changes in the incident radiation (PAR) and air- and soil temperature which has impact on the photosynthetical activity (CO_2 flux) and respiratory processes.

As seen from Fig. 3, two characteristic shoulder-seasons mark the transition to the season of net uptake of CO_2. The seasonal variation in abiotic forcing can be used to divide the year into five characteristic parts: i - winter; ii - spring thaw; iii - pre-green; iv - green; v - post green (Aurela *et al.*, 2001).

During winter (i) the ground is snow covered and soil temperatures are below 0°C, which result in small losses of CO_2 from the ecosystem. This period is usually not very well documented in Zackenberg, but as seen from Fig. 4 the 2005 season provided a period of winter time measurements. The flux at this time of year is seen to be relatively stable.

In the spring thaw period (ii), snow cover may act as a trap for CO_2. Micro-organisms are protected from the extreme variations in air temperature, and are able to produce more CO_2, than they would if they were exposed to the air temperatures. Oechel *et al.*

(1997) found that respiratory processes continued during winter at soil temperatures down to -7°C.

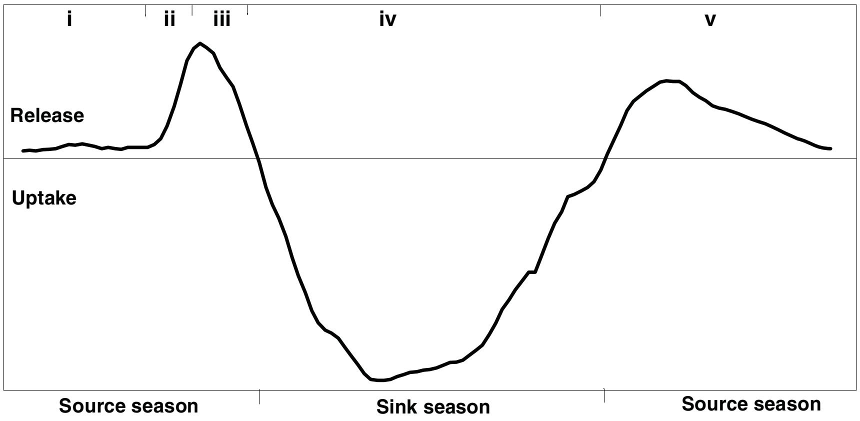

Figure 3. A schematic visualisation of the seasonal carbon exchange in the Arctic. Data resembles the seven years of measurements from Zackenberg.

During this period a maximum release of CO_2 is seen. The release at the spring thaw is probably related to the build-up of CO_2 produced prior to the thawing event and consequently released upon thawing as a combination of release of the enhanced heterotrophic decomposition under the disintegrating snow cover and physical release due to thawing of the active layer. Physical release of stored CO_2 has previously been detected when snow-melt is occurring and the top soil layer melts (Friborg *et al.*, 1997).

During the pre-green period (iii) the net ecosystem exchange increases, and the CO_2 flux start to show a diurnal pattern. At this early stage of the summer season the amount of solar radiation is at its peak which is important for the development of the plants and the photosynthetic process.

In the growing season (iv), the plants start developing leaves. In this period the ecosystem switches from a source to a sink in response to the increased photosynthesis, and the ecosystem constitutes a sink with a net daily uptake of CO_2. During this period uptake of CO_2 is observed almost 24 hours of the day, due to the 24 hours of incoming radiation (Nordstroem *et al.*, 2001; Paper I). The uptake of CO_2 is tightly linked to canopy development, and NEE increases with increasing leaf area (Soegaard & Nordstroem, 1999). When leaf area index starts to decrease, the net uptake diminishes, and the plant senescence becomes more and more significant. As the night gets longer, the night-time losses of CO_2 become more frequent and more marked. Eventually the ecosystem turns into a source of CO_2, and the post-green period (v) begins, which characterises the autumn. This period is characterized by large effluxes of CO_2 to the atmosphere. As seen from Fig. 4, this period is poorly documented in Zackenberg. The source season constitutes by far the longest time interval of the annual C-cycle. The length of the winter and autumn consequently exerts strong control on the annual budget.

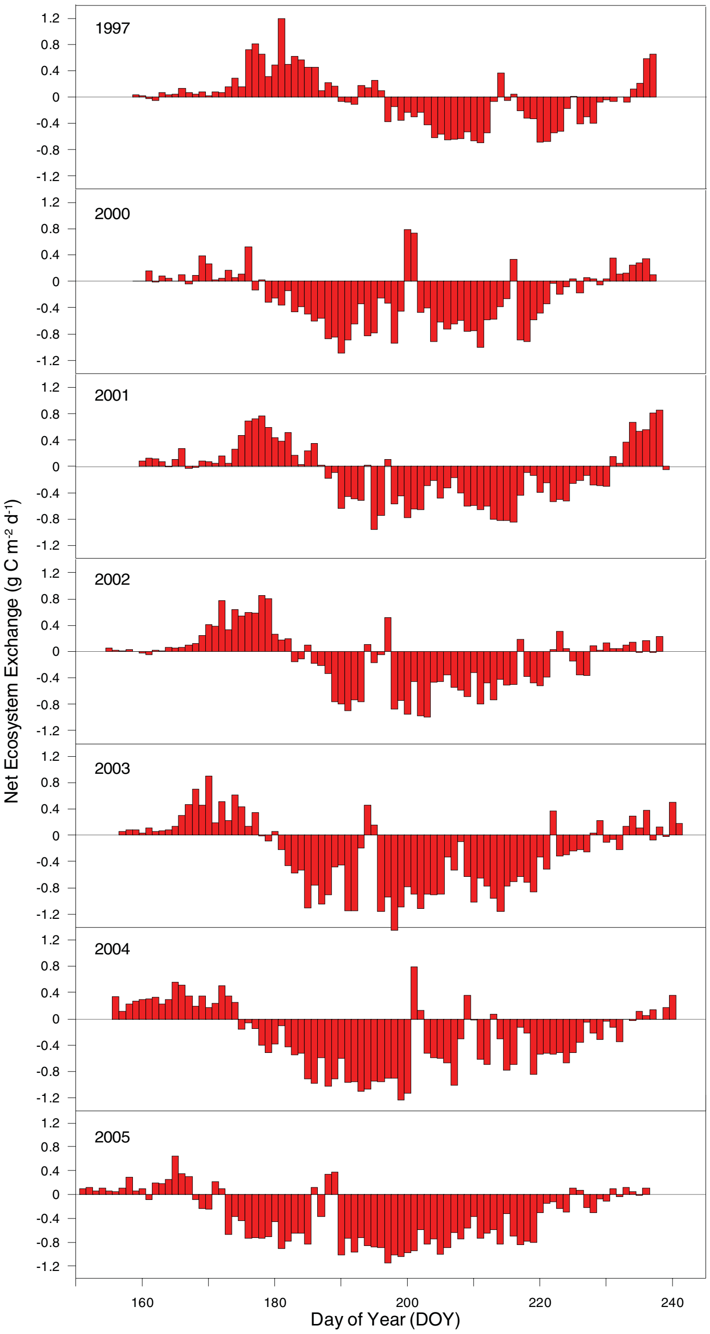

Figure 4. The seasonal development in daily integrated NEE during seven years of measurements in Zackenberg. Modified from Paper I.

As seen from Fig. 4 the start of the sink season is markedly different during the seven years. This is caused by the timing of snow-melt. Since 2001 the progressively earlier timing of the snow-melt has lead to an earlier start of the uptake (Paper I). The springtime temperature has a significant impact on the snowmelt in the area, explaining 93% of the variation in snowmelt (Paper I). A warm spring will favour an advanced snow melt. The incoming radiation at this time of year is favourable for the photosynthesis, which will lead to an early start of the uptake and increase the length of the growing season. If temperatures during the growing season are high, increased uptake during the growing season has been documented (Paper I). The difference between spring start up and autumn senescence is of great importance for the ecosystem in a source/sink perspective.

During the autumn the decreasing radiation levels initiates the senescence and the shortening of the day further decreases the daily uptake rates of CO_2. High autumn temperatures would favour respiratory losses and possibly lead to net decrease in the annual C-budget. The length of each of the seasons is critical to the annual budget (Paper V).

3.2 Interannual variation

The net annual exchange of CO_2 is determined by the strength of the net release in the source seasons, relative to the strength of the net uptake in the sink season.

At other research sites in the Arctic the seasonal C-balance during the summer period have been documented to vary from year to year, from net sink to net source of CO_2, from one year to another (e.g. Lloyd, 2001b), depending on the meteorological conditions. This is not the case in Zackenberg, where the time series of measurements have shown a net sink situation during the summer period, although the strength has varied from year to year (Paper I).

It was found that the uptake rate during the summer correlated well with the characteristics of the spring conditions, where early snow-melt tends to increase summer time uptake rates (Fig 5).

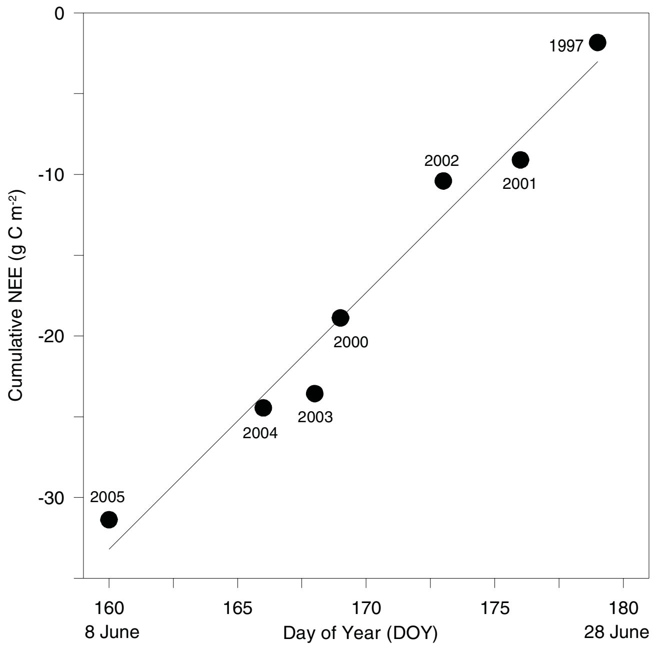

Figure 5. Cumulative NEE from DOY 159 to DOY 238 for all seven years plotted against day of snow-melt at the snow sensor. $R^2 = 0.97$, $p<0.0001$.

Also the number of growing degree days during the summer period had a significant correlation with uptake rates. Temperature was found to positively affect NEE. As seen from Fig. 6, the summed growing degree days correlated with the seasonal uptake of CO_2 during all seven years (Paper I). The interannual differences in growing season NEE were found to be explained by variations in GEP, as the photosynthetic component was found to be affected positively by the temperature.

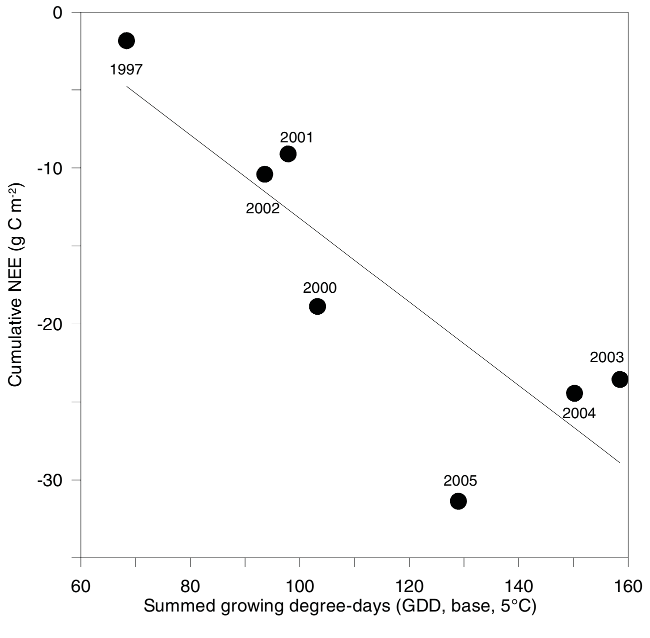

Figure 6. Cumulative NEE From DOY 159 to 238 for all seven years vs. the summed growing degree-days. $R^2 = 0.71$, $p=0.017$.

The main explanation for this might be found in the fact that the ecosystems in Zackenberg are at their northern limit (Havstrom *et al.*, 1993) and therefore responds positively to the increment in summer time air temperature seen during the past decade (Paper I). This is contrasting to previous findings in Alaska, where Vourlitis & Oechel (1999) found that respiration was the main explanatory component in interannual variation.

Ecosystems' source/sink strength may be affected by different climatic conditions for respiration and photosynthesis in the five characteristic periods, as described above (Joiner *et al.* 1999). Climatic conditions that favour a strong summer sink, may be offset by other climatic conditions in the source periods that favour respiration. Furthermore, the ecosystem's source/sink strength is likely to be affected by variable temporal extension of the five characteristic periods. A long growing season has potentially greater sink strength, than a short growing season (Paper V).

3.3 Comparison of methods

During the 2004 growing season an experiment was carried out to examine the relationship between spectral reflectance and CO_2 exchange at five different vegetation types. It was consequently interesting to examine if the measurements from the eddy covariance technique and the chamber technique were comparable, in order to be able to scale the measurements to integrate the fluxes at landscape level. In Paper II the two methods were compared using a footprint approach and a reasonable agreement (81%) between the two methods was found. The two methods corresponded well during the peak of the growing season, which is attributed to the development of the vegetation in the relatively small plots. It was found that difference in development of the vegetation might explain the clear difference in flux magnitude at the beginning and the end of the growing season. Until the vegetation was fully developed the eddy covariance method yielded the largest flux. Light attenuation might be another factor explaining the difference in fluxes. Plexiglas chambers have previously been found to dampen the light by approximately 10% (Vourlitis *et al.*, 1993) and Roehm *et al.* (2003) found that 87% of incident PAR was transmitted through the plexiglas chamber. It can therefore be expected that there might be some attenuation of the incident PAR in the measurements performed in

Zackenberg, which might contribute to explain why the agreement between the two method differ at the beginning and end of the season.

3.4 Fluxes from different vegetation types

The heterogeneity in the species composition, soil properties and hydrology of Arctic ecosystems influences the flux pattern of the ecosystems. In Paper II large differences were shown between the measured fluxes in five dominating vegetation types in the Zackenberg valley. The fen was the far most productive vegetation type, having uptake rates of up to 900 mg $CO_2m^{-2}h^{-1}$. Contrasting are the less productive *Cassiope* and *Dryas* sites. These two sites constitute 42.3% of the area in the Zackenberg valley in comparison the fen covers approximately 15% of the area covered by vegetation (Paper III). The obtained fluxes from the five vegetation types are consistent with other daytime measurements published from Zackenberg using manual chambers (Christensen *et al.*, 2000; Joabsson & Christensen, 2001).

Continuing the trend towards a warmer climate, a change in the vegetation composition is expected at high latitudes. A northward migration of the vegetation is expected to result in a prolongation of the growing season and increased vegetation productivity. Thawing of permafrost and warming and deepening of the soil active layer with associated large changes in hydrology are also expected (ACIA, 2005). There is increasing evidence that these changes are already occurring across large portions of the Arctic (Hinzman *et al.*, 2005). Increasing temperature has shown to give more pronounced responses in High Arctic sites compared to lower latitude sites in the Arctic. Enhanced coverage of the sparse vegetation (i.e. *Dryas*) has been observed at increasing temperature levels, which in turn might lead to increased photosynthetic uptake rates, providing the nutrient supply is adequate (Callaghan *et al.*, 1999). Evidence of changing vegetation in the Arctic has been documented by Tape *et al.* (2006), who found an increase in shrub coverage over a 50 years period. The distribution of snow in the Zackenberg valley is expected to influence the vegetation composition, Hinkler (2005) predicts increased snow fans in the area leading to an increased areal coverage of the snowbed communities. Changes in the distribution of the snow coverage and duration of snow free period are expected to alter the distribution of the *Cassiope* heath and the *Salix* snowbed communities. However, at present no change in the distribution of these two vegetation types has been found (Bay, 2006). A survey on changes in vegetation composition is conducted every 5 year in Zackenberg. The recent survey reveals that a major snow-fan has decreased in size, which might have implications for the vegetation reliant on the water supply from the fan. There were, however, no signs of changes in the vegetation at the site (Bay, 2006). Hypothesing whether changes in vegetation would occur in Zackenberg under the predicted changes in climate, might imply that the dwarf shrub heath vegetation would become denser i.e. increase leaf area and consequently increase the CO_2 uptake.

However, the climate change scenarios for the 21st century also predict increasing precipitation, which would favour the grassland areas developing into fen areas. Contrary if precipitation decreases in the region and the summer period becomes drier, the fens might dry out and turn into the less productive grasslands. In northern Sweden, Malmer *et al.* (2005) found the decreasing permafrost resulted in an expansion of graminoids dominated vegetation, whereas the shrub dominated hummocks receded in areal extend over a 30 years period. Increased soil moisture could increase anaerobic decomposition leading to increased methane emissions and consequently tip the delicate balance in the area.

3.5 Upscaling the CO_2 fluxes

C-exchange in the Arctic region has been studied at a few locations, covering some of the ecosystems in the region. However, still large areas remain to be studied, as the C-exchange in the Arctic previously has been shown to vary substantially, due to variations in climate and other environmental factors. Moreover regional budgets are not easily assessed, due to lack of flux measurements from the various ecosystems that comprises the tundra. Upscaling of fluxes from the major ecosystems in a region provide a valuable tool for assessing regional budgets, which can be utilised in monitoring of the carbon status of the Arctic.

Eddy covariance and chamber measurements are the key to characterising the CO_2 fluxes at sub-regional scales; these data are small area values; i.e. they are representative of relatively small discrete patches in space. Regional scale estimates may be made by extrapolation of these “point” data over time and space, although errors could result from such extrapolations if fluxes are controlled by a different set of factors at each scale.

In Paper II an attempt to derive a model based on spectral reflectances and NEE at plot-scale was tried. However owing to the different mechanisms which regulate photosynthesis and respiration, it was interesting to investigate whether separating the sub-components of the CO_2 exchange would improve the estimated NEE. Therefore an attempt to model GEP and ER was performed in Paper III. Based on the assumption that PAR is the dominant factor controlling the uptake of CO_2 in addition with the ability of the vegetation to assimilate CO_2 (described by NDVI), a simple model based on a hyperbolic function was applied. The respiration was assumed to be most influenced by temperature, but also NDVI (Paper III). This approach has been successfully applied in Alaska (Oechel *et al.*, 2000; Vourlitis *et al.*, 2003). The overall agreement between measured and modelled GEP and ER was 89% and 74%, respectively. NEE was estimated from the derived GEP and ER for each of the vegetation types derived in the region, based on a landcover map of the major vegetation types in the region derived from a Landsat TM image. The Landsat image had an overall accuracy of 82% which is satisfactorily for the Arctic (Mosbech & Hansen, 1994). The estimate on NEE improved from 65% (Paper II) to 88% (Paper III). This is not surprising as the physiological processes driving GEP and ER are dependent on abiotic factors which was included in the modelling seen in Paper III. The simple model can therefore be used when upscaling fluxes to regional level. However, due to the growing seasonal temperature dependence of NEE as seen in Paper I, the models are site and year specific, i.e. they need adjustments every year and cannot be transferred to other regions in the Arctic. Upscaling NEE was additionally tried by weighting the fluxes with their areal coverage derived from the classified Landsat TM scene. It was found that in the High Arctic, with large topographical differences the simple model was the approach describing the difference in fluxes most correctly taking into account the decreasing vegetation density with increasing altitude.

In total the Zackenberg area gained CO_2 during the 2004 growing season (Paper II; III). This is in correspondence with findings from the Kuparuk River Basin in Alaska, where the region was estimated to be a small sink of CO_2 during the growing season, on the annual basis however the area was a net source (Oechel *et al.*, 2000).

Finally in Paper IV the individual components of the C-exchange are integrated using data from terrestrial (wetlands and dwarf shrub heaths), fluvial and coastal ecosystems and with additional measurements of CO_2 exchange over the Greenlandic sea. The results show that this High Arctic locality is an important carbon sink also when the methane emission is taken into account.

3.6 Changes in circumpolar CO_2 flux

The complexity in the response of the Arctic circumpolar tundra ecosystems to climate change is described in Paper V. Determining the present status of the Arctic tundra as a source or a sink of CO_2 is difficult, due to the scarcely represented study localities in the region (Paper V). Long term measurements on C-exchange in the Arctic are scarce; the timeseries from Zackenberg does however increase our present knowledge on the response of Arctic ecosystems to changes in abiotic factors. Compared to research conducted in other parts of the Arctic region, the Zackenberg area seems to increase uptake rates in all vegetation types in response to the observed increasing temperatures during the past decade (Paper I; II; III; IV).

In northern Alaska the effects of the changes in climate are different to those of NE Greenland. The increasing temperature and additional increase in growing season length over the last 3-4 decades have resulted in that ecosystems in this region shifted from being net sinks to net sources of CO_2. This is however contrasted by the wetter parts of the area, which through two seasons functioned as net sinks of CO_2 (Harazono *et al.*, 2003) The difference in dynamics between the ecosystems found in the region has a strong impact on growing season sink strength. Studies in the Boreal and Arctic ecosystems indicate that wetness and temperature are important factors in determining the growing season NEE. Wet summers are often associated with strong sinks of CO_2 for the wet ecosystems whereas dry summers are associated with weak sinks and are sometimes even sources of CO_2 (Shurpali *et al.*, 1995; Lafleur *et al.*, 2003). The findings in Zackenberg however contradict the previous findings. The strongest sink activity occurred in the driest and warmest of the years of measurements, whereas a wet year had an intermediate uptake and the coldest year had the weakest sink (Rennermalm *et al.*, 2005).

Although studies of C-exchange have only been conducted at a few localities there have been indications that vast areas are at present losing carbon to the atmosphere during the summer season in Siberia and Alaska e.g. (Oechel *et al.*, 1993; Heikkinen *et al.*, 2004). This is indicative for the very delicate balance in the Arctic ecosystems as they are sensitive to changes in temperature and water table depth e.g. (Heikkinen *et al.*, 2002). For the circumpolar north it was found that the region is in balance (Paper V).

4 Concluding remarks and perspectives

Predicting the effects of global climate warming is of international importance, as climate is not restricted to small areas, but encompasses the entire globe. The work presented in this thesis contributes to the understanding of the ecological impacts of climate change on CO_2 exchange in the High Arctic.

Net Ecosystem CO_2 Exchange was measured between the atmosphere and the High Arctic tundra in Zackenberg. The measurements were conducted using different methods, the eddy covariance (EC) technique at a dry dwarf shrub heath and the chamber technique, covering five different vegetation types. This provided a continuous time series of data from the dry heath and detailed information on the CO_2 exchange from the different vegetation types.

The results from the monitored ecosystems in Zackenberg have documented that they are sinks of CO_2 during the growing season. The long-term measurements using the EC technique showed that the dry dwarf shrub heath is strongly dependent on early snow-melt, which was shown to prolong the growing season and if air temperatures are high during this period, the uptake rates are increased. The interannual variation in cumulated growing seasonal Net Ecosystem CO_2 Exchange uptake rates was found to range from -1.8 gCm^{-2} to -31.4 gCm^{-2}, during the years 1997, 2000-2005. Using footprint analysis it was shown that the two techniques corresponded during the peak of the growing season. Due to the large coverage of the Arctic region and the logistical constraints on obtaining flux measurements from the vast areas in the region, a challenge is to assess regional budgets. A simple model and area weighting of fluxes was used jointly with a vegetation map to upscale the fluxes to a regional budget. This showed that the region during the summer season is a net consumer of CO_2 during the growing season.

However, as the monitoring so far only documents the growing season in the area, the critical periods determining whether the ecosystem on an annual basis is a source or a sink are lacking. The loss of CO_2 during the autumn is crucial to the annual status along with the winter-time fluxes. Consequently measurements from these seasons are needed for a conclusive answer on the current status in this ecosystem. Additional measurements covering other landcover types e.g. the fen with high temporal resolution EC measurements would be needed in order to evaluate the future climatic changes in this area.

In conclusion it seems that this part of the High Arctic is increasing uptake rates as temperature increases, the balance is however delicate and even minor climatic changes e.g. changes in precipitation or temperature, might have severe effects on the CO_2 exchange.

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Paper I

Groendahl, L., Friborg, T. and H. Soegaard

Temperature and snowmelt controls on the carbon
exchange in a high arctic ecosystem

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Temperature and snow-melt controls on interannual variability in carbon exchange in the high Arctic

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With 6 Figures

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Summary

Net Ecosystem CO_2 Exchange (NEE) was studied during the summer season (June–August) at a high Arctic heath ecosystem for 5 years in Zackenberg, NE Greenland. Integrated over the 80 day summer season, the heath is presently a sink ranging from $-1.4\,\mathrm{g\,C\,m^{-2}}$ in 1997 to $-23.3\,\mathrm{g\,C\,m^{-2}}$ in 2003. The results indicate that photosynthesis might be more variable than ecosystem respiration on the seasonal timescale. The years focused on in this paper differ climatically, which is reflected in the measured fluxes. The environmental conditions during the five years strongly indicated that time of snow-melt and air temperature during the growing season are closely related to the interannual variation in the measured fluxes of CO_2 at the heath. Our estimates suggest that net ecosystem CO_2 uptake is enhanced by $0.16\,\mathrm{g\,C\,m^{-2}}$ per increase in growing degree-days during the period of growth. This study emphasises that increased summer time air temperatures are favourable for this particular ecosystem in terms of carbon accumulation.

1. Introduction

According to Maxwell (1992) climate change is expected to be most pronounced in the Arctic areas. The recent focus from ACIA (Arctic Climate Impact Assessment) and IPCC (Intergovernmental Panel on Climate Change) has added to the awareness of the effects of the increasing global temperature on the Arctic ecosystems. During the last century the land surface temperature (north of 60° N) has increased by approximately 0.9 °C (McBean et al., 2004) and the scenarios from IPCC expect the Arctic ecosystems to experience changes due to increasing temperature and precipitation in the future (IPCC, 2001). Moreover model studies reveal large geographical variations in the Arctic region in annual temperature response to predicted global warming and in NE Greenland, projected annual surface temperature, is expected to increase between +2 to +4 °C during the period 1990 to 2090 (Huntington et al., 2004).

How the terrestrial ecosystems in the high Arctic regions respond to change in temperature is not well known, and the scarcity of data, especially from the High Arctic, causes difficulties in predicting whether these areas are sources or sinks of CO_2. However, some predictions on how the Arctic region will be affected by climate change have been proposed. If increased temperatures cause earlier snow-melt, the onset of vegetation growth will occur earlier in spring. This might extend the length of the growing season and probably increase carbon sequestration, as in temperate forests, where an average increase in CO_2 uptake of $5.7\,\mathrm{g\,C\,m^{-2}}$ per day in growing season was found by Baldocchi et al.

(2001). Conversely, if precipitation increases in the form of snow, timing of snow free conditions might decrease the growing season, hence carbon sequestration might decrease (Petersen et al., 2001). Areas underlain by permafrost are, in particular, sensitive to increased warming, as increased active layer depth is likely to increase respiratory release of carbon dioxide from the soil (Maxwell, 1992). An understanding of the responses to the predicted temperature rise and increased active layer depth in the region is needed in order to predict the future status of the carbon balance in the Arctic region. According to Jonasson et al. (2001) differences of 1–2 weeks in time of snow-melt or growing season mean temperature differences of less than 1 °C are very significant for carbon sequestration in the Arctic ecosystems. Similarly, Shaver and Kummerow (1992) argued that the major factor controlling the onset of growth interannually in the arctic ecosystems is the timing of snow-melt and above-freezing temperatures.

During the past years, there has been a focus on whether the circumpolar tundra ecosystems, constitutes a source or a sink for CO_2. While the majority of these studies have been carried out in wet and moist ecosystems in the low Arctic region, such as Alaska and Siberia (Oechel et al., 1993, 1995; Oechel and Vourlitis, 1994; Vourlitis and Oechel, 1997, 1999; Harazono et al., 1998, 2003; Heikkinen et al., 2002), while dry ecosystems in the Arctic have been less investigated (Jones et al., 1998). The High Arctic is an important part of the Arctic region, according to data from Bliss and Matveyeva (1992), the ice-free part of the High Arctic covers an area of approximately $2.4{*}10^6\,km^2$, which constitutes 42% of dry ecosystems (semi-desert and polar desert). During the last decade the high Arctic region in Greenland has been subjected to studies on the carbon balance during the growing season, in Zackenberg, NE Greenland (Christensen et al., 2000; Illeris et al., 2003; Nordstroem et al., 2001; Soegaard and Nordstroem, 1999; Soegaard et al., 2000). In addition, carbon dioxide fluxes from a High Arctic dry ecosystem in Svalbard have been presented (Lloyd, 2001a, b).

Reported measurements of carbon dioxide flux in Arctic ecosystems during the last three decades have given a diverse picture of the C-balance in the region (Stieglitz et al., 2000). Oechel et al. (1995) showed that a wet sedge ecosystem in Alaska changed from a sink to a source during the period 1971 to 1992. Results from the entire Kuparuk River Basin in 1995–1996 showed that the area was a net CO_2 source of 218.1 GgC (Oechel et al., 2000).

However, in the recent decade, measurements from a moist tussock tundra ecosystem in Alaska indicates that the ecosystem is now a net sink (Vourlitis and Oechel, 1997, 1999). These results imply large differences between ecosystem types and sensitivity even to small changes in climate. Hence, it seems that the impact of climatic change might vary between ecosystems and the interannual responses of the ecosystem to the variation is diverse, resulting in the ecosystem being a net source of CO_2 one year and a net sink of CO_2 the next year (Oechel et al., 1993; Zimov et al., 1996; Vourlitis and Oechel, 1997, 1999; Stieglitz et al., 2000). Hence, an understanding of the factors controlling the flux of carbon from arctic areas is essential for predicting how these regions will respond to global change (Hobbie et al., 2000).

In order to achieve broader knowledge on carbon exchange in the High Arctic, micrometeorological measurements were initiated in Zackenberg in 1997 (Soegaard et al., 2000). Carbon fluxes have been monitored every summer since 2000, contributing to the evaluation on the climatic response of a high Arctic dry heath ecosystem by providing a time series of CO_2 flux data.

This paper presents the Net Ecosystem Exchange (NEE) from the high Arctic dry heath ecosystem in Zackenberg, measured using the eddy covariance technique, during the period from early June until late August. We investigated the temperature impact on the carbon balance of a dry heath ecosystem, expecting temperature to constrain the carbon exchange.

2. Methods and materials

2.1 Site description

The Zackenberg research area (74°28′N, 20°34′W) is located in the north-eastern part of Greenland. According to Bliss and Matveyeva (1992) the area is within the High Arctic zone characterised by a mean temperature below 5 °C in July and annual precipitation varying from 148–236 mm water equivalent (Rasch and Caning, 2003).

The area of the low-lying part of Zackenberg valley (below 200 m.) is approximately 17 km^2. The valley consists of three dominating ecosystem types: fen, willow snowbed and heath. The heath ecosystem covers approximately 5.5 km^2 corresponding to 31% of the valley (Soegaard et al., 2000). The plant coverage on the heath is sparse, *Cassiope tetragona* (White Arctic Bell-heather), *Dryas integrifolia* (Mountain Avens) and *Vaccinium uliginosum* (Arctic blueberry) dominate the heath ecosystem, accompanied by patches of mosses, *Salix artica* (Arctic willow) and *Eriophorum scheuchzeri* (Cotton grass). This vegetation composition is floristically representative for large parts of NE Greenland. Maximum single-sided Leaf Area Index (LAI) reached 0.2–0.3 at the heath during the peak of the growing season, whereas in the moist ecosystems in the valley it may reach 1–2 (Soegaard et al., 2000).

The valley has a northern border at a narrow pass and a fjord to the south. The eastern and western parts of the valley are bound by mountain ridges with altitudes of approximately 1500 m. The topographic impact on the local wind is seen from the dominating wind direction. NNW winds are dominant most of the year. In summer, from June to August, the wind direction is SSE. Land sea breeze occurs throughout the summer. Summer wind velocities ranges from 3–4 ms^{-1}.

The area is underlain by permafrost, which disintegrates during the summer season, and the activelayer at the heath increases to approximately 70 cm. Soil temperatures above zero are found from mid June until late August.

2.2 Measurements

In the five years 1997, 2000–2003, micrometeorological measurements of CO_2 exchange were conducted from the first week in June, while snow still covered the surface until the last week in August. Thus, the measurements included the entire growing season at this site. The study site at the heath was established in 1997 (Soegaard et al., 2000). In the period from 2000 onwards measurements were conducted every summer within the ZERO (Zackenberg Ecological Research Operations) programme.

2.3 Instrumentation

As described by Soegaard et al. (2000) CO_2 exchange was monitored by the eddy covariance technique. A mast is equipped with a 3D sonic anemometer, Solent 1012R2 (Gill Instruments, Lymington, United Kingdom) placed 3 m above the surface and a closed-path infrared gasanalyser (Licor 6262, LI-COR, Nebraska, USA). Raw data from the system was logged at 21 Hz on a portable computer equipped with the EdiSol software (Moncrieff et al., 1997). For post-processing of the fluxes a 200 s running mean of wind and scalar components were used and windspeeds were axis rotated in order to prevent flow distortion/effects on the vertical wind speed from landscape obstacles and misalignment of the anemometer according to Mcmillen (1988). Fluxes were calculated as 30-min averages. Corrections in the fluxes were applied for frequency loss (Moore, 1986), attenuation of the CO_2 signal in the tube and effects of water vapour on the CO_2 signal (Webb et al., 1980). A detailed description of the instrumental setup, flux calculation and correction routines can be found in Moncrieff et al. (1997). Typical errors for this instrumental setup under the climatic conditions in Zackenberg were according to Soegaard et al. (2000) found to be ±7% of NEE or ±7 mg CO_2 m^{-2} h^{-1} during mid-season in the present study.

A total of 80 days are reported here from each season. Gaps originating from instrumental malfunctioning, equipment maintenance and calibration resulted in 8.9% of the data was missing in 1997, 0.8% in 2000, 1.4% in 2001, 0.9% in 2002, and 2.4% in 2003. Gap-filling was performed in accordance with Falge et al. (2001); gaps <2 h were filled by linear interpolation between earlier and later measurements. Longer time periods were filled by binned half-hourly values computed from a 6-days period surrounding the gap.

The energy balance components during the time of snow-free conditions (July to August) for the heath site is composed of the sensible, latent and ground heat fluxes. During this period, the energy balance closure resulted in a negative residual that, on average, during the five years constituted 9% of the net radiation.

The eddy covariance mast was located at the *Cassiope t.* dominated heath with a fetch of approximately 1000 m in all directions. The permanent climate station, approximately 200 m SSW of the eddy covariance mast, supplied the additional meteorological data such as air temperature at 2 m height, precipitation, net and global radiation. In addition, snow depth and depletion was monitored (SR50 Ultrasonic Sensors, Campbell Scientific, USA) and ortho-photos of the central part of the study area provided snowcover images. Detailed information on the measured variables are found in the ZERO annual report (Rasch and Caning, 2004).

2.4 Flux components

The measured CO_2 flux between an ecosystem and the atmosphere referred to as NEE, is the balance between plant uptake of CO_2 through photosynthesis and respiratory loss of CO_2 from plant and soil (Ruimy et al., 1995)

$$\mathrm{NEE} = (\mathrm{R_a} + \mathrm{R_h} - \mathrm{GEP}) = \mathrm{R_{eco}} - \mathrm{GEP} \qquad (1)$$

where GEP is the gross ecosystem photosynthesis, R_a is the autotrophic respiration consisting of contributions from leaf respiration, respiration from the stem and woody parts of the plants and root respiration. The heterotrophic respiration flux, R_h, derives from the decomposition of organic material by micro-organisms in the soil, also referred to as soil respiration. The sum of the heterotrophic respiration and autotrophic respiration constitutes the total ecosystem respiration, R_{eco}.

2.5 Respiration

In order to determine ecosystem respiration, R_{eco}, we used an empirical exponential relationship between measured CO_2 flux at night-time and the soil temperature. Assuming that the ecosystem respiration response to soil temperature applied at day-time, we used the derived regression models to extrapolate ecosystem respiration to the entire season. The regression models are year specific, i.e. they cannot be applied to other years.

3. Results

3.1 Meteorological conditions during the five years

A summary of air temperature, global radiation and precipitation is presented in Table 1. Large differences were seen between thaw, pre-green, green and the post-green period mean daily air temperatures. The air temperatures in the thaw period 2002 was notably high, 2.2 °C, which was approximately 1 degree higher than the other years. Differences between air temperatures are also seen in the green period, where the mean daily air temperature in 2003 provided a strong contrast to the other years.

Table 1. Monthly average values of global radiation ($W\,m^{-2}$), air temperature (°C) and precipitation (mm) in 1997, 2000–2003

	1997	2000	2001	2002	2003
	by phenological period and year				
Mean daily air temperature (°C)					
Thaw	1.14	1.3	0.77	2.18	1.22
Pre-green	3.75	3.97	3.5	3.35	3.04
Green	5.47	4.97	5.71	5.93	7.39
Post-green	3.34	5.06	5.9	4.15	5.15
Mean daily global radiation ($W\,m^{-2}$)					
Thaw	165	303	255	409	284
Pre-green	219	307	293	295	320
Green	207	213	226	181	192
Post-green	180	142	122	117	131
Total precipitation (mm)					
Thaw	22.9	3.2	25.4	73.9	85.2
Pre-green	25.2	0.3	0.2	0	0.3
Green	10.8	13.2	3.8	25.6	9.2
Post-green	0.1	0	11.4	0.5	0.3

In 2002, global radiation levels during the thaw period were high compared to the other years. However, due to periods of poor weather during the green period the average global radiation was below the levels received during the other years in this period.

Precipitation in this high arctic area is characterised by a few very intensive events each summer: on average, 32 mm falls every year from the time when snow has melted in June/July to the end of August. In 1997, the pre-green period was characterised by rain events originating from storms passing the area during July and the green period received precipitation on most days. During the post-green period in 2001 the area received 11.4 mm precipitation, which was a strong contrast to the other years. A wet green period characterised 2002 and the heath received 25.6 mm rain.

Snow depth and day of snow-melt varied between the five years. Snow-melt rates were calculated from the monitored snow depths at DOY 140 (20 May), when global radiation albedo was at a maximum (0.80), indicating that snow had not begun melting. Therefore, we assumed that the densities of the snow packs were identical during the five years. In 1997, snow persisted until DOY 179 which was 10 days longer than 2003. This was attributed primarily to lower air temperatures during the period of melt. We defined the melting potential of the snow from a degree-day model, using the summed hourly air temperatures above −2 °C ($((\Sigma T_{a,\,hour} \geq -2\,^{\circ}C)/24)$). As seen from Fig. 1, the snow depth at DOY 140 correlated strongly with cumulative degree-days, confirming temperature as a significant snow-melt factor. The considerable variation in snowdepth, from 0.48 m to approximately 1 m, resulted in an average melt-rate of 7.4 mm/degree-day amongst the years, which explained 93% of the variation.

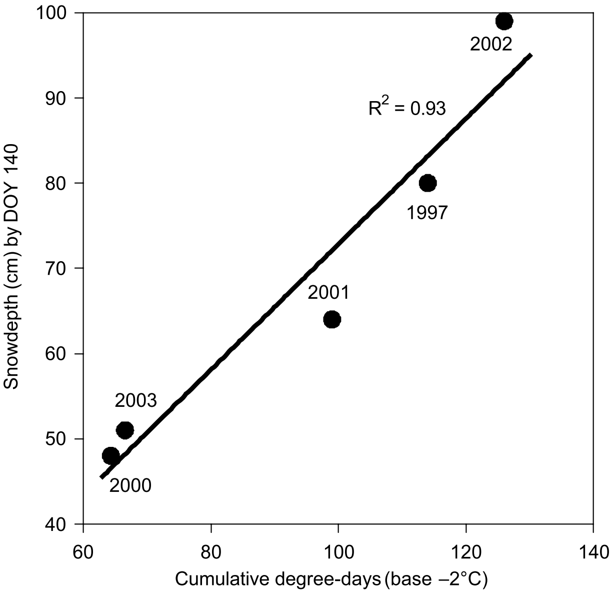

Fig. 1. Snowdepth (cm) at DOY 140 versus the cumulative degree-days with base −2 °C, from DOY 140 until the snow had melted

3.2 Study periods and definition of phenological periods

In this study, data from the years 1997 and 2000–2003 were analysed. Each year, CO_2 fluxes at the heath were measured in the interval from the first week in June until the last week in August, covering the thaw and the growing periods. For comparative purposes, data are presented for all years covering an 80 day season (DOY 159–238) in this study referred to as summer season. The season was divided into 4 periods (Table 2), following the seasonal changes in daily integrated NEE as well as variations in global radiation albedo, temperature and phenological development.

The thaw period was characterised by melting snow cover and during this period the global radiation albedo decreased as the snow progressively melted and soil temperatures increased as a result. This period always showed positive daily NEE values, indicating a respiratory loss of CO_2. The pre-green period was a period of transition, defined from the time when the global radiation albedo was below 0.1 and from visual inspection of photos to determine when the snow had melted in the micrometeorological mast fetch area. During this period air temperatures increased and the daily integrated NEE was positive. However, the vegetation progressively started photosynthesising during the latter part

Table 2. Phenological period for each year in the study

	1997	2000	2001	2002	2003
Day of Year for each phenological period					
Thaw	159–179 (8 June −28 June)	159–169 (7 June–17 June)	159–176 (8 June–25 June)	159–173 (8 June–22 June)	159–168 (8 June–17 June)
Pre-green	180–193 (29 June–12 July)	170–176 (18 June–24 June)	177–187 (26 June–6 July)	174–182 (23 June–1 July)	169–177 (18 June–26 June)
Green	194–233 (13 July–21 August)	177–226 (25 June–13 August)	188–230 (7 July–18 August)	183–227 (2 July–15 August)	178–232 (27 June–20 August)
Post-green	234–238 (22 August–26 August)	227–238 (14 August–25 August)	231–238 (19 August–26 August)	228–238 (16 August–26 August)	233–238 (21 August–26 August)

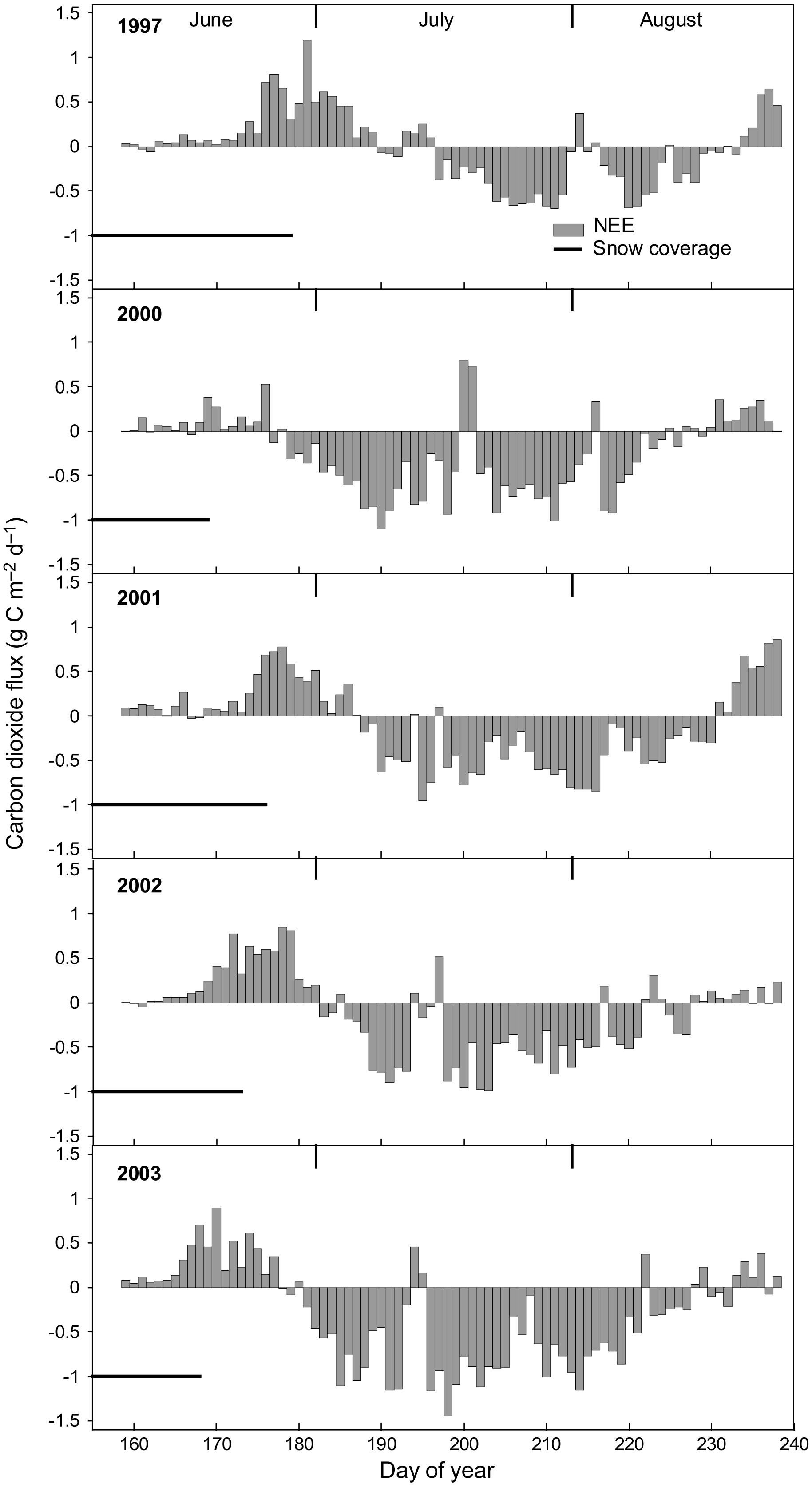

Fig. 2. Daily integrated NEE of carbon dioxide ($g\,C\,m^{-2}\,d^{-1}$) for the years 1997 and 2000–2003

of the period. As daily integrated NEE turned from a net source to a net sink the green period began, this was the period of net growth. During this period the vegetation turned green and the LAI progressively increased to a maximum of approximately 0.3 (Soegaard et al., 2000). The length of the green period varied from five weeks in 1997 to eight weeks in 2003 (Table 1). During the post-green period, the ecosystem respiration exceeded the photosynthesis and daily integrated NEE showed a net loss. This period was characterised by decreasing soil and air temperatures as well as decreasing global radiation levels.

3.3 Net ecosystem exchange

The daily integrated sums of NEE ($\mathrm{g\,C\,m^{-2}\,d^{-1}}$) during the five years of measurements at the heath is seen in Fig. 2. Using the micrometeorological sign convention, downward directed flux of CO_2 from the atmosphere to the surface is negative, denoting an ecosystem sink and thus positive values denote a source of CO_2. Respiratory losses increased as soil temperatures progressively increased.

The seasonal amplitude during the period from June to August is clearly seen in Fig. 2. Respiratory losses of CO_2 during the pre-green and post-green periods delimit the net CO_2 gain during the green period. In 1997 and 2002 the daily average NEE in the pre-green period was $0.5\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$, whereas the pre-green period in 2000 only had a small respiratory loss of $0.2\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$.

In the green period with the strongest sink strength, the average daily integrated NEE ranged between $-0.3\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$ in 1997 and approximately $-0.6\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$ in 2003. Onset of and uptake of CO_2 from the atmosphere varied by three weeks during the five years, whereas the end of the green period varied by only a few days. In 1997 the first day of net uptake was DOY 194 (13 July) and in comparison the uptake of CO_2 began on DOY 177 (25 June) in 2000. The end of the green period varied from DOY 226 (13 August) in 2000 to DOY 232 (20 August) in 2003, which caused a distinct difference in

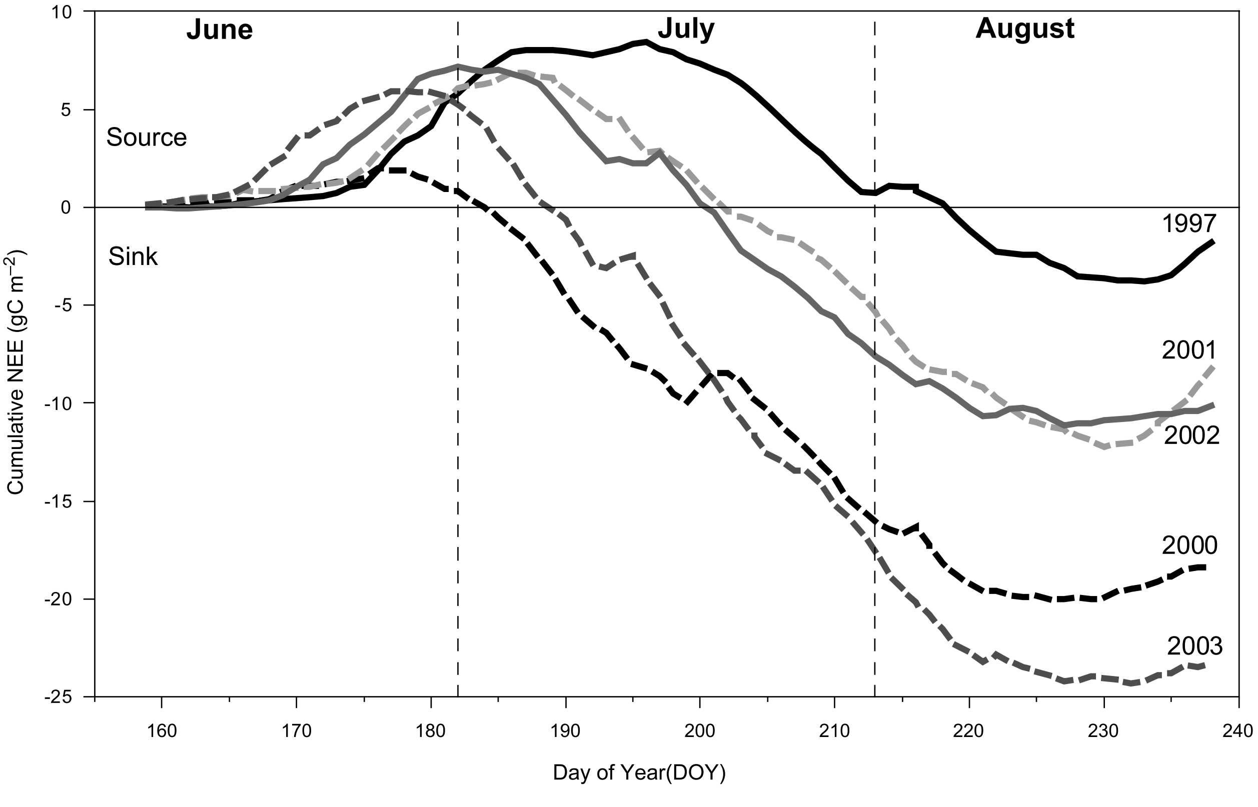

Fig. 3. Growing season cumulative net ecosystem CO_2 exchange ($\mathrm{g\,C\,m^{-2}}$) during 5 seasons of measurements at a high Arctic heath in Zackenberg NE Greenland

the length of the green period of 39 days in 1997 and 54 days in 2003.

Each year, periods of poor weather (usually periods of rain) reversed the fluxes and the ecosystem became a source of CO_2 for a short period.

Maximum daily integrated NEE was seen in the period from DOY 190 to DOY 199, except in 1997, which had a maximum daily integrated uptake at DOY 220 and coincided with the highest daily average air temperatures.

The vegetation senesced during late August and the respiratory losses exceeded the plant uptake of CO_2. NEE during the post-green period varied from daily average losses of $0.06\,g\,C\,m^{-2}\,d^{-1}$ in 2002 up to $0.5\,g\,C\,m^{-2}\,d^{-1}$ in 2001.

3.4 Variation in cumulative NEE

Cumulative net ecosystem CO_2 exchange during the five years of measurements is shown in Fig. 3. During 1997 monitoring period, cumulative NEE showed a net gain of carbon by DOY 238 of $-1.4\,g\,C\,m^{-2}$. The large effluxes of CO_2 seen in the pre-green period (Table 3) originated from the high heterotrophic respiration, associated with increasing soil temperatures and release of CO_2 from the thawing soil. Losses increased from DOY 159 until the end of the pre-green period by DOY 196. In the green period, the photosynthesis exceeded R_{eco} and the heath gained $-11.4\,g\,C\,m^{-2}$ (Table 3). Throughout the post-green period, from DOY 234 until the end of the measurements by DOY 238, the heath lost $2\,g\,C\,m^{-2}$.

Table 3. Cumulative net ecosystem CO_2 exchange ($g\,C\,m^{-2}$) for each phenological period and year

	1997	2000	2001	2002	2003
Thaw	0.7	0.4	1.2	0.4	0.7
Pre-green	7.3	1.6	5.6	6.8	5.3
Green	−11.4	−22.5	−19.1	−18.1	−30.3
Post-green	2.0	1.6	4.0	1.0	1.0
Summer season	−1.4	−18.9	−8.3	−9.9	−23.3

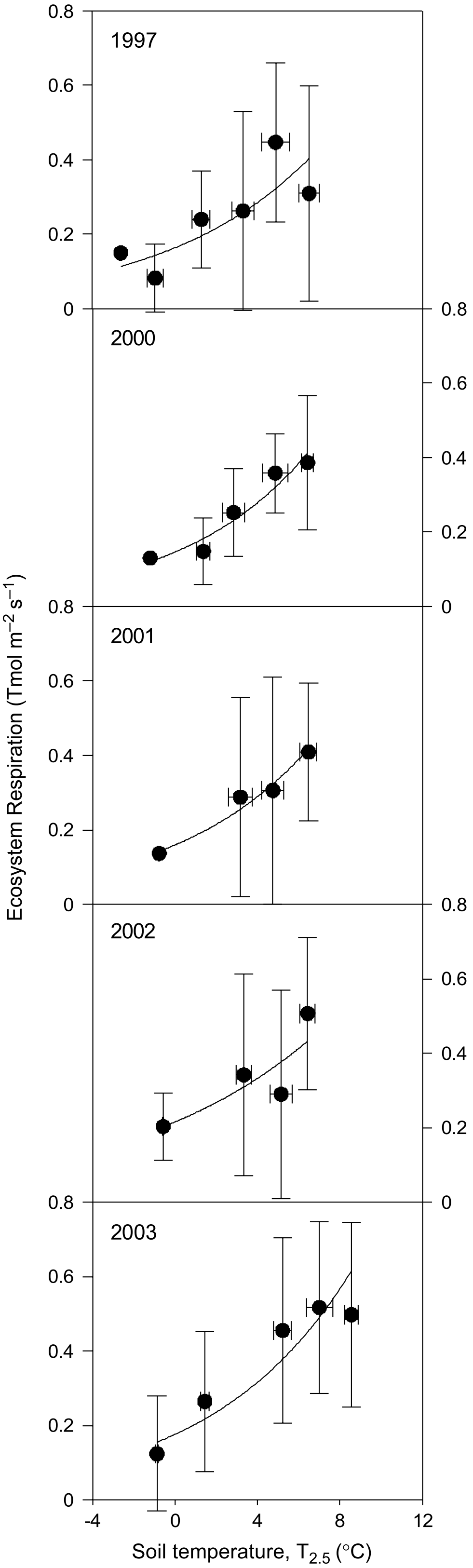

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Fig. 4. Estimated ecosystem respiration versus soil temperatures at 0.025 m depth ($T_{2.5}$), during the five years. Exponential regression in 1997 ($0.1637\,e^{0.1388x}$; $R^2 = 0.66$, $p = 0.050$), 2000 ($0.1463\,e^{0.1611x}$; $R^2 = 0.93$, $p = 0.009$), 2001 ($0.1549\,e^{0.149x}$; $R^2 = 0.97$, $p = 0.015$), 2002 ($0.2155\,e^{0.1085x}$; $R^2 = 0.76$, $p = 0.128$), 2003 ($0.1762\,e^{0.1462x}$; $R^2 = 0.88$, $p = 0.017$)

In 2000 the heath gained $-18.9\,\mathrm{g\,C\,m^{-2}}$ in the 80 day measuring period. Photosynthesis exceeded R_{eco} by DOY 177 and photosynthesis remained larger than R_{eco} until DOY 226, except for a few days in July, where poor weather resulted in a small reduction in cumulative NEE. However, the heath remained a net sink of carbon throughout this period.

During the summer season 2001 the heath gained $-8.3\,\mathrm{g\,C\,m^{-2}}$. During the thaw when the microbial activity was low there was a small respiratory release of CO_2 and also in the pre-green seasons the cumulative NEE was positive. The heath had a gain of carbon from DOY 188 until DOY 230, of $-19.1\,\mathrm{g\,C\,m^{-2}}$.

Cumulative net exchange of carbon during 2002 showed a strong similarity to the 2001 season. During the summer season, the heath gained $-9.9\,\mathrm{g\,C\,m^{-2}}$ in total. Following the same pattern as the 2001-season, the heath lost 88% of the total seasonal loss during the thaw and pre-green seasons. By DOY 183 the photosynthesis exceeded R_{eco} and the heath started gaining carbon.

The 2003 season showed some similarity to the 2000 season. However, the loss of $5.3\,\mathrm{g\,C\,m^{-2}}$ through the pre-green period is larger than in the 2000 season. This is accomplished by the gain during the green period, where cumulative gain was $-30.3\,\mathrm{g\,C\,m^{-2}}$. The variation in NEE during this period was closely related to canopy development (Soegaard and Nordstroem, 1999), NEE increased as LAI increased. By the end of the summer season at DOY 239, the net cumulative gain was $-23.3\,\mathrm{g\,C\,m^{-2}}$.

3.5 Ecosystem respiration, R_{eco}

Using the eddy covariance technique, direct measures of ecosystem respiration and photosynthesis are not available. However ecosystem respiration can be estimated from the night time fluxes (Lavigne et al., 1997). Hence, to reveal the ecosystem response to the climatic differences during the five years, the ecosystem respiration and the residual GEP were analysed using parameterisations with a simple empirical regression model.

Figure 4 shows the relationship between ecosystem dark respiration, obtained from night-time eddy covariance measurements during periods of low levels of incident radiation, and soil temperatures at 2.5 cm depth, $T_{2.5}$. Estimating ecosystem respiration from eddy covariance data at a high Arctic site is complicated by the incoming radiation, received 24 hours a day from 1 May until 8 August. Hence we defined night-time as incident short-wave radiation $<20\,\mathrm{W\,m^{-2}}$, assuming photosynthesis to be inactive at this level.

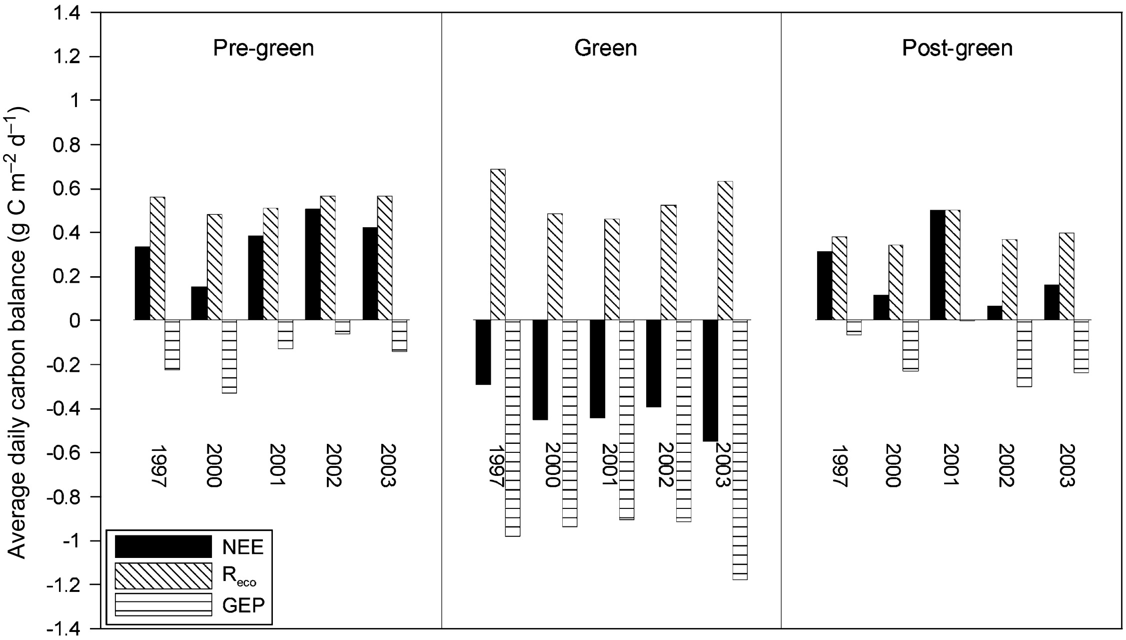

Fig. 5. Average daily NEE, R_{eco} and GEP ($\mathrm{g\,C\,m^{-2}\,d^{-1}}$) for each phenological period and year

Reliable night-time measurements of fluxes require adequate mixing of air. Often low wind speed prevail at night and as such, there might be an inhibition of the mixing (Lavigne et al., 1997). Therefore, we used data from the night-time periods with a friction velocity threshold of $u^* > 0.1\,\mathrm{m\,s^{-1}}$. Due to the length of the day at this high latitude, the criteria used for selecting the appropriate data for the models limited the number of available data ($n = 58$ in 1997; 98 in 2000; 70 in 2001; 65 in 2002 and 145 in 2003). Data available to examine the relationship were scattered, probably due to seasonality in the fluxes, as seen from the standard deviation hence to obtain a clear relationship between soil temperature and nocturnal eddy covariance data, averages of 30-min fluxes were binned in 2 °C intervals (Fig. 4). Soil temperatures in 2.5 cm depth accounted for 66% of the variance of R_{eco} in 1997 and 99% in 2001, which is in accordance with findings from Alaska (Harazono et al., 2003). Models derived for all years were significant at the 0.05-level, except 2002 which was probably due to the limited number of points ($n = 4$). Pearson's correlation showed that the correlation between the obtained models for 2001 and 2003, and 2002 and 2003 were not statistically significant. The derived relations were used to calculate R_{eco} during the growing season for each of the five years. Assuming that the ecosystem respiration during day-time could be estimated by the derived exponential relationships, GEP was estimated as the residual.

Average daily NEE, R_{eco} and GEP for the pre-green, green and post-green period are seen from Fig. 5.

4. Discussion

4.1 Interannual variability in NEE

The results presented here show that there are large interannual differences in net ecosystem CO_2 exchange during the five years of study, which are caused by the variability in climatic conditions. The largest interannual variability in cumulative NEE is found during the post-green period (Table 3). However, the total seasonal cumulative NEE varied approximately 2.5 fold between the seasons 2001 and 2002 compared to 2003, whereas 1997 varied by 12.9 fold (Fig. 3). The interannual variability in NEE is driven by change in the photosynthetic uptake of the dwarf shrubs and respiratory loss by the ecosystem. The residual GEP rates were generally more variable than the estimated R_{eco} rates through all three periods (Fig. 5). We, therefore, assume that the variation in NEE is largely driven by changes in rate of photosynthesis rather than respiration. This is supported by another study in Zackenberg in 1997 (Christensen et al., 2000).

The uptake of CO_2 is controlled overall by radiation for the photosynthetic process. We, however, did not find any correlation between global radiation levels and cumulative NEE during the study period. However, Semikhatova et al. (1992) reported that arctic plant species are adapted to their environment, enabling photosynthetic capacity at low light levels. Moreover, Semikhatova et al. (1992) argued that photosynthesis proceeds at near-maximum rates over a broad range of temperatures, reporting optimum temperatures ranging from 10°–25 °C in the Russian Arctic. Further, Shaver and Kummerow (1992) and Oechel and Billings (1992) supported this, arguing that the temperature at which arctic plants grow are rarely optimal even for these

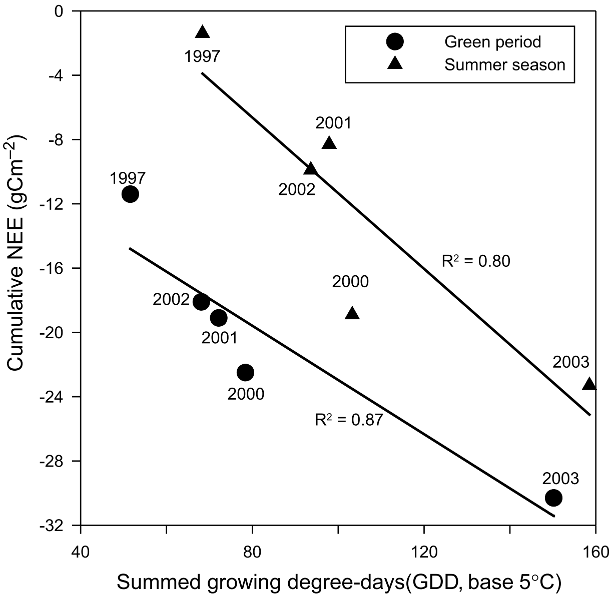

Fig. 6. Cumulative NEE during the green period and the summer season (June–August) versus summed degree-days (base 5 °C). Regression lines are shown as solid lines (green period, -0.169×-6.105, $R^2 = 0.87$; summer season $-0.235 \times +12.192$, $R^2 = 0.80$)

highly adapted species. Hence, when examining summed growing degree-days (GDD) and cumulative NEE, a clear ecosystem response to increased temperatures is seen (Fig. 6). We defined GDD according to Maxwell (1992), who found the growing season for plants to be climatically defined by the total number of degree-days above 5 °C. This definition was also used in the study performed by Aurela et al. (2001a, b) in Finland. We modified GDD slightly and calculated summed degree-days from hourly temperatures exceeding 5 °C divided by 24, to a daily basis. The predictive power of this correlation is very robust, as variation in GDD accounts for 87% of the variance in observed cumulative NEE during the green period (Fig. 6). Timing of snow-melt constrained the length of the green period and hence had a strong impact on cumulative NEE during this period. The smallest cumulative NEE of $-11.4\,\mathrm{g\,C\,m^{-2}}$ was seen in 1997 when snow had melted by DOY 179. This was contrasted by the largest uptake of $-30.3\,\mathrm{g\,C\,m^{-2}}$ in 2003 when snow had melted by DOY 168.

This is further supported by findings from a subarctic fen in Finland (Aurela et al., 2004), where snow-melt timing was concluded to be the most important factor controlling the annual carbon balance. Similarly, a strong correlation ($R^2 = 0.8$) is found between summer season (June–August) cumulative NEE and summed GDD (Fig. 6). Hence, we hypothesise that this particular high arctic ecosystem has a strong temperature control on NEE. This is consistent with the findings of Havstrom et al. (1993), who found positive growth response in *Cassiope t.* to increased temperature, this effect was increased with latitude.

The temperature based ecosystem respiration models are presented in Fig. 4. The respiratory rates are in accordance with results from chamber measurements at a heath site in the Zackenberg research area (Elberling et al., 2004), suggesting that the empirical relationship is representative for this ecosystem. The variation in respiratory rates is satisfactory, R^2 values ranged between 0.66 and 0.99, which justifies the use for this specific site. The estimated R_{eco} during the green and post-green periods varied between $0.4\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$ and $0.7\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$, which are comparable to findings from the few other studies in the high Arctic (Christensen et al., 2000; Elberling et al., 2004; Illeris et al., 2003; Jones et al., 2000). Chamber measurements from a *Cassiope t.* dominated heath site in Zackenberg showed respiration rates ranging between 1 and $2.1\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$ (Christensen et al., 2000). However, the respiratory fluxes reported by Christensen et al. (2000) were measured between 10:00 and 15:00 hours, where top-soil temperatures are expected to be highest, which might explain the large differences from the daily averaged R_{eco} values in this study. An experiment in Zackenberg found respiration rates at a dry *Cassiope* heath ranging between 0.3 and $1.07\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$ (Illeris et al., 2003). From a polar desert in NW Greenland Jones et al. (2000) found respiratory rates ranging from 0.1 to $0.9\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$. Whiting et al. (1992) found, from chamber measurements in Alaska, values of total ecosystem respiration of approximately $1\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$.

We found that precipitation had an impact on NEE. During days with rain in the green period the flux reversed and the ecosystem acted as a source of CO_2 (Fig. 2). Similarly, Illeris et al. (2003) found respiratory losses of CO_2 from the dry heath surface in Zackenberg, fast and significantly after rain events, and related the response to the increased microbial activity. Hence, the respiration at the heath might be constrained by the sparse precipitation events during the summer season.

4.2 Growing season budget

The length of the green period varied from 36 days in 1997, with a cumulative NEE of $-11.4\,\mathrm{g\,C\,m^{-2}}$ up to 54 days in 2003, resulting in a cumulative NEE of $-30.3\,\mathrm{g\,C\,m^{-2}}$. Hence, NEE is expected to enhance on average by $1\,\mathrm{g\,C\,m^{-2}}$ per increased day in green period. Green period length was controlled by the day of snow-melt. Thus, earlier snow-melt is expected to increase the length of the green period and increase carbon accumulation. The length of the analysed summer season was 80 days during the five years, with a 12.7-fold increase in cumulative NEE from 1997 to 2003 (Fig. 6).

The variability in sink strength within ecosystems is however an issue which needs further attention to be able to predict the precise impact of future climate warming. Timing of snow-melt and air temperature in addition with frequency of rain events are the major parameters that control the carbon balance of this ecosystem. Lloyd (2001b) showed that a high arctic semi-dessert ecosystem shifted from being a summer sink to a source the next year due to variability in environmental parameters. Many of the performed studies in the Arctic have been conducted during the summer seasons. Therefore, many annual budgets are based on summer fluxes. However, carbon losses from the Arctic ecosystems have been shown to be significant during winter (Fahnestock et al., 1999; Oechel et al., 1997; Zimov et al., 1996). Hence, measurements during winter and autumn are critical in our understanding of the carbon balances in the Arctic ecosystems. Results from a study on wet and moist tundra in Alaska showed that the winter time respiratory loss accounted for 70% of the annual respiration (Oechel et al., 1997), while in other ecosystems inclusion of winter time losses of CO_2 into the annual budgets increased the annual respiratory loss by 17% (Fahnestock et al., 1999).

The respiratory loss during winter from the 1997 season at the heath in Zackenberg, was modelled by Soegaard et al. (2000), resulting in an area integrated loss of $6.5\,\mathrm{g\,C\,m^{-2}}$ $\mathrm{season^{-1}}$, assuming respiration as a function of temperature. Assuming that the respiratory loss does not change interannually, this result, coupled with our present study, indicates that NEE at the heath is in balanced on an annual basis. However, understanding and quantifying the annual carbon budgets of high arctic ecosystems, more studies on wintertime fluxes are needed in order to conclude on the ecosystem source/sink strength. Modelling of annual carbon balance for the heath by Soegaard et al. (2000) indicated an area integrated loss of $5.2\,\mathrm{g\,C\,m^{-2}\,y^{-1}}$ in 1997. The carbon balance was constituted by an area-integrated sink of $-7.1\,\mathrm{g\,C\,m^{-2}}$ $\mathrm{season^{-1}}$ during the green period and a loss during the rest of the year of $12.3\,\mathrm{g\,C\,m^{-2}}$ $\mathrm{season^{-1}}$. The 1997 summer season was dominated by poor weather. Although mean daily air temperatures and global radiation levels seem comparable to the other years, the resulting cumulative growing degree-days were low. In addition, the frequently occurring rain events during the 1997 green period might have increased the respiratory losses. Hence, the sink strength was expected to be smaller as seen from Fig. 3.

5. Conclusion

The response of the high Arctic ecosystems to climate change is uncertain. The sporadic study of carbon dioxide exchange from different Arctic and high Arctic ecosystems in addition to the short period of research from these sites makes it difficult to observe long-term changes in these ecosystems. A diverse pattern of carbon dioxide exchange is seen throughout the Arctic region, this study however indicates that the heath in Zackenberg during the observed summer season has a net uptake of carbon dioxide. From the presented results, we conclude that in this particular ecosystem the photosynthesis responded stronger to increased temperatures than ecosystem respiration. Hence, uptake of CO_2 increased as growing degree-days increased. However, this relation only applies if soil moisture does not increase. Our results confirm that the air temperature expressed as growing degree-days are critical to the sink/source strength of this particular ecosystem. From the results it can be observed that the ecosystem sink strength increases by $-0.16\,\mathrm{g\,C\,m^{-2}}$ per increase in growing degree-days (base 5 °C) during the green period. Similarly, van Wijk et al. (2003) found a reduction in annual gross primary production of $4\,\mathrm{g\,C\,m^{-2}\,y^{-1}}$ per day at the start of growing as the season was delayed in a tussock tundra ecosystem. However, the sink strength on an annual basis is debatable, given the lack of measurements during especially autumn but also winter. Hence, we can conclude that temperature has a strong impact on the dry heath ecosystem in Zackenberg, increasing the summer season sink strength. The interannual variation in summer season NEE originated mainly from the variations in date of snow-melt and the air temperatures during the green period. Summed melting degree-days explain 93% of the variation in snow-melt (Fig. 1). In a climate change perspective this is important, since this area, according to the climate model, is subject to increased annual temperatures. Increased temperatures might lead to increased accumulated

NEE and probably also increase the length of the growing season.

In contrast to the studies performed in wetlands in the arctic region, where ecosystems respond quite variably to increased temperatures (Oechel et al., 1993; Zimov et al., 1996; Vourlitis and Oechel, 1997, 1999; Stieglitz et al., 2000), we have demonstrated that this particular ecosystem seems to benefit from increased summer temperatures.

Acknowledgement

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Scaling CO_2 fluxes from plot- and field-level to
landscape-level in a high arctic ecosystem using a
footprint model and satellite images

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Scaling CO_2 fluxes from plot- and field-level to landscape-level in a high arctic ecosystem using a footprint model and satellite images

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Running title: Upscaling Net Ecosystem CO_2 Exchange

Key words: Chamber Method, CO_2 exchange, Eddy Covariance Method, Footprint Model, High Arctic Ecosystems, NDVI, Satellite Images, Upscaling, Vegetation Map

Abstract

Within the High Arctic Zackenberg valley, NE Greenland, the Net Ecosystem CO_2 Exchange (NEE) was studied during the growing season 2004. During this period, chamber method measurements were performed in five dominating vegetation types for nine weeks. Additionally eddy covariance measurements were performed on a dry heath from the time of snowmelt until the end of August.

We performed a cross scale analysis of the measurements from plot-level (chambers) and field-level (eddy covariance) to landscape-level, using a footprint model, a digital vegetation map and satellite images. Scaling of chamber measurements from plot-level to field-level, using the footprint model had an overall agreement of 81%, clearly indicating that the plot-level measurements correspond with the field-level measurements, during the time of actively photosynthesising vegetation. A simple regression model was derived from the relationship between Normalised Difference Vegetation Index (NDVI) and NEE at plot-level with an overall agreement of 65%. Estimating landscape-level NEE from the plot-level measurements was performed by weighted the individual vegetation type fluxes according to their areal contribution within a 5km^2 area. Compared with satellite derived NEE using the regression model a good correspondence was found. Comparing eddy covariance derived NEE and satellite derived NEE large difference were seen in the early part of the growing season, a satisfactory correspondence was however found at the peak of the growing season.

Consequently, during the summer period a footprint model, a vegetation map and satellite images are reliable products for scaling NEE from plot-level to landscape-level.

During the nine week period of measurements, the 5km^2 area constituted an integrated mean daytime sink of 166.3 mgCO$_2$ m^{-2} h^{-1}. The cumulative summer season NEE for

the eddy covariance data showed that the dry heath ecosystem was a net sink of 83.9 gCO_2 m^{-2}.

Introduction

The global change scenarios predict the High Arctic region to be highly affected by climatic changes in the near future (Maxwell B., 1992; Serreze *et al.*, 2000; IPCC, 2001). In fact, recent studies document that climate changes already are occurring (ACIA, 2005). Covering an area of approximately $1.98*10^6$ km^2 and holding a carbon stock of 2.35 PgC (1 PgC = 10^{15} gC) (Bliss & Matveyeva, 1992) the High Arctic region plays an important role in the global carbon cycle. Mobilising these reserves due to climatic changes could alter the feedback mechanisms resulting in net losses of stored carbon. Consequently, during the last decades, landscape studies of carbon exchange from Arctic ecosystems have been performed in Alaska (Whiting *et al.*, 1992; Oechel *et al.*, 1998; Williams *et al.*, 2000; Vourlitis *et al.*, 2000b) and also Siberia have been subject to intensive field studies (Zimov *et al.*, 1993; Zamolodchikov *et al.*, 2003). The results indicated that the ecosystem in Barrow, Alaska lost 1.3 gC m^{-2} y^{-1} during the growing season in 1992 compared to an estimated gain of 25.1 gC m^{-2} y^{-1} during the 1971 growing season (Oechel *et al.*, 1995). However the most recent studies from the Kuparuk River Basin in Alaska shows that the area has a summer seasonal uptake of 0.1 $\pm$ 5.5 gC m^{-2} (1994-1996)(Oechel *et al.*, 2000). The High Arctic region in Greenland has in the recent decade been subject to field-level studies of CO_2 exchange between the terrestrial ecosystem and the atmosphere during the growing season (Soegaard *et al.*, 2000; Nordstroem *et al.*, 2001). Results from this area indicate that the high arctic fen ecosystem is a sink of 28.1 gC m^{-2} during the growing season (Nordstroem *et al.*, 2001). The high arctic heath ecosystem in the Zackenberg research area has been shown to be a summer season sink with gains ranging between 1.4 gC m^{-2} and 23.3 gC m^{-2} (Groendahl *et al.*, in press), whereas the entire ecosystem in the Zackenberg valley constituting an area of 16.2 km^2 is a summer season sink with a gain of 18.8 ± 6.7 gC m^{-2} (Soegaard *et al.*, 2000).

Different methods have been applied when measuring CO_2 exchange. At field-level the eddy covariance technique has been used and at plot-level the chamber method has been used (Whiting, 1994; Vourlitis & Oechel, 1997; Christensen *et al.*, 2000; Griffis *et al.*, 2000; Vourlitis *et al.*, 2000a; Illeris *et al.*, 2003). The two techniques provides complementary information and they are both essential in the understanding of the dynamics of the ecosystem and the spatial and temporal variability in the fluxes measured (Oechel *et al.*, 1998; Vourlitis *et al.*, 2000a). However, the techniques may not provide similar results, due to the difference in scale. While the eddy covariance technique measures at hectare scale providing a continuous time series of CO_2 exchange from a given source area (the footprint) with possible contributions from several vegetation types, the chamber method provides detailed information on a small part of the ecosystem (Oechel *et al.*, 1998). There are weaknesses in both techniques. The eddy covariance technique is the most technically demanding of the two and interpretation problems have been experienced under stable atmospheric conditions and advection (Lapitan *et al.*, 1999; Reth *et al.*, 2005). The chamber technique has the disadvantage of a possible disturbance of the measured vegetation plot each time a measurement is performed (Hooper *et al.*, 2002). In addition the spatial and temporal resolution of CO_2 exchange from chambers is limited and may therefore not be representative for the ecosystem as a whole (Oechel *et al.*, 1998). Comparing the two techniques using a footprint model provides a tool for upscaling the fluxes to a regional level.

The use of satellite images enables modelling of the CO_2 exchange on a regional scale, giving opportunity for monitoring of the effects of climate change on remotely located arctic ecosystems. The Normalised Difference Vegetation Index (NDVI) has been proposed as a valuable tool in detecting and quantifying large-scale changes in plant and ecosystem processes associated with global change (Hope *et al.*, 2003; Jia *et al.*, 2003). A few studies have previously examined the feasibility of using remote sensing in monitoring the biosphere/atmosphere CO_2 exchange rates by a simple relationship between CO_2 exchange and NDVI (Whiting *et al.*, 1992; Whiting, 1994; McMichael *et al.*, 1999). A footprint approach was used in the evaluation of a simple NEE- NDVI regression model for the Arctic tundra environments in Alaska (Hope *et al.*, 1995). When applying the models to satellite data, spatial and temporal patterns of the CO_2 exchange are provided. This enables long-term monitoring of the potential feedback associated with climate-change-induced alteration in arctic ecosystems C sequestration on a regional scale (Oechel *et al.*, 2000; Vourlitis *et al.*, 2003).

In the High Arctic only few attempts have previously been made in scaling the CO_2 flux from plot to field level and to our knowledge no direct relation between spectral reflectance and CO_2 exchange at plot-level has been applied to satellite images for a scaling of the fluxes to landscape-level. In this study, we present measurements from the plot-level chamber method and the field-level eddy covariance technique from the summer season 2004. We conduct a cross scale analysis and aim at evaluating the CO_2 exchange within an area in NE Greenland by relating plot-level fluxes placed at five vegetation types to field-level fluxes from the eddy covariance system, using a footprint model and a vegetation map. Secondly, we relate plot-level fluxes with a spectral vegetation index and test this robust method to estimate CO_2 flux on landscape-level by use of a satellite image.

Materials and methods

Research site.

The Zackenberg research area is located in a valley in NE Greenland as seen from Fig. 1. The valley is dominated by five main vegetation types (fen, *Dryas octopetala x integrifolia* heath*, Cassiope tetragona* heath, *Salix arctica* snowbed and grassland). In total, these cover approximately 70% of the area classified by Bay (1998).

Zackenberg is located in the High Arctic climate zone, with a mean monthly temperature in July of 5.5°C and a mean precipitation of 36 mm from June to late August (Table 1). Continuous permafrost underlay the area with an active layer depth of approximately 70cm during summer (Rasch & Caning, 2004). The regional climate is strongly influenced by the fjord to the south of the area; land-sea breezes dominate the wind pattern throughout the summer, oriented north-south parallel to the mountain ridges.

Study periods

In the study period in 2004, CO_2 flux measurements were conducted during the growing season which at this high arctic locality extended from early June until late August. We employed the eddy covariance equipment in the period from 4 June (DOY 156) while snow was still covering the surface until 28 August (DOY 241). In addition repeated chamber measurements were performed in 15 vegetation plot sites once a week during nine weeks from 23 June (DOY 175) until 19 August (DOY 232) as part of the SCHAPPE project (Spectral Calibration of High Arctic Primary Production Estimation) (Tamstorf *et al.*, in prep).

Plot-level instrumentation and measurements

Chamber measurements were undertaken during the snowfree period at five different vegetation types, which were representative of the vegetation types found in the footprint of the eddy covariance mast. Plot level measurements of CO_2 exchange was conducted using a portable EGM-4 infrared gas analyser (PP Systems, UK) connected to a transparent acrylic chamber of 13.6 litres. A circulation fan ensured thorough mixing of the chamber air. Aluminium bases with an inner ground area of 0.038 m^2 equipped with a water channel to ensure airtight seal were inserted into the soil. Measurements were performed once a week in each plot. At each plot two sets of measurements were conducted, one in daylight (Net Ecosystem Exchange) and one in darkness (Ecosystem Respiration). The EGM system logged 11 consecutive measurements of chamber CO_2 concentration, air temperature, humidity and photosynthetic active radiation (PAR) over a period of 3 minutes and 20 seconds. After each set of measurement the chamber was briefly removed from the base in order to restore the CO_2 level to ambient. When replaced on the base, the chamber was covered with a dark bag to exclude all light and a new measurement was performed as above. This measurement yielded the ecosystem (plant plus soil) respiration (ER). The measured ecosystem fluxes were corrected at each individual plot for the exact chamber volume and calculated in units per square meter. The chamber flux (FC) was calculated as:

$$FC = \frac{\Delta CO_2}{\Delta t} \tag{1}$$

where ΔCO_2 is the change in CO_2 concentration over the Δt, 3.33 minute interval. The selected vegetation plots were located in the five dominant vegetation types found in the Zackenberg area, with three sites in each of the five types: *Cassiope* heath, *Dryas* heath, *Salix* snowbed, fen and grassland (Fig. 1). The dominant species in each of the plots and their areal coverage is presented in Table 2. For logistic reasons simultaneous measurements of Net Ecosystem CO_2 Exchange (NEE) at each site of the five vegetation types were not possible. Therefore, the flux from each of the vegetation types was calculated as an average for each week (Fig. 2), with about four measurements days per week (Table 3). Each site had one plot for the CO_2 measurement and one for the canopy reflectance measurement. Additional measurements of canopy reflectance were conducted on the CO_2 plots at each site during the latter part of the season (3 August – 18 August). The majority of the chamber measurements were taken between 10:00 and 16:00 hours on days of sunny and cloud-free weather conditions.

By convention, Net Ecosystem CO_2 Exchange is considered negative in sign, when the net CO_2 flux is directed from the atmosphere to the ecosystem and thus a gain to the ecosystem, whereas the fluxes directed from the ecosystem are positive (ecosystem loosing carbon dioxide).

Field -level net CO_2 flux measurements

Eddy covariance measurements of CO_2 were conducted at a *Cassiope tetragona* dominated heath site (Fig. 1). Details of the flux measurements have been reported previously (Soegaard *et al.*, 2000; Groendahl *et al.*, in press). The eddy covariance method was used to measure the concentrations of CO_2, H_2O and temperature, using a three-dimensional sonic anemometer for measuring wind speed and wind direction (Gill Solent, Gill Instruments, UK) and an closed-path Infra Red Gas Analyser (IRGA) (LiCor 6262, LiCor Inc., USA). The sampling tube of the IRGA and the sonic anemometer was located in 3m height above the heath surface. Fluxes were calculated using a 200s running mean of axis rotated, vertical wind speed according to the routines described in Moncrieff et al. (1997), and corrected for frequency loss, attenuation of CO_2 signal in the tube and effects of water vapour on the CO_2 signal. Details on instrumentation and typical errors ($\underline{+}$ 7% of Net Ecosystem CO_2 Exchange) can be found in Soegaard et al. (2000). In total 85 days of measurements were collected during the 2004 growing season. Gaps originating from instrumental malfunctioning, equipment maintenance and calibration resulted in 1% missing data. Gaps were filled by linear interpolation (gaps < 2h) between the previous and the following measurements. Longer time periods were filled by binned half-hourly values computed from a 6-days period surrounding the gap. Flux convention is the same as described for the plot-level measurements.

According to the formulation by Gash (1986) the upwind footprint in any direction under neutral conditions was in the order of 150 m for 50% of the total flux contribution and about 590m for 85% of the total flux contribution.

In addition, three soil heat flux plates (HFT-3, REBS Inc., Campbell Scientific Inc., UK) were installed at 1cm depth. Additional data on meteorological variables were obtained from the meteorological masts providing year round data from the Zackenberg valley site. Net radiation (Rn) (CM7, Kipp & Zonen, The Netherlands) was measured at a height of 2m. Energy-balance closure was used to assess the performance of the eddy covariance flux system. Closing the energy balance perfectly, the sum of the sensible and latent heat fluxes (H + Le) measured by the eddy covariance is equal to the difference between the net radiation and the ground heat flux (Rn – G) measured independently from the eddy covariance equipment. The least squares regression based on two weeks binned half-hourly averages of the components (n=288; y=0.96 x+9.27; R^2=0.82) resulted in a relationship between the two components with a slope that was 4% lower than unity, indicating a small under-estimation in H+Le.

Radiometric measurements

Canopy reflectance was measured with a FieldSpec Handheld Spectroradiometer (Analytical Spectral Devices Inc., Boulder, USA) at the CO_2 exchange plots from week 6 (Table 3). The spectroradiometer was mounted on a tripod measuring vertically downwards to the surface at approximately 44cm height. The Field of View (FOV) had a diameter of 19.5cm. Measurements of a spectralon 99% standard reflectance panel were made before each set of canopy measurements, used for correction to true reflectance.

The measured spectra were resampled corresponding to Landsat-7 ETM+ spectral bands and the NDVI was derived from reflectances in the red ETM 3 (630-690 nm) and near-infrared ETM 4 (750-900 nm) channels using the following expression NDVI = (ETM 4- ETM3)/(ETM4 +ETM 3).

Footprint model and scaling procedure

The interpretation of the CO_2 fluxes measured by the eddy covariance technique has limitations as to the contributing source areas. Therefore, by using a footprint model, information regarding the extension of the up-wind source area can be obtained.

A theoretical distribution of the footprint was formulated by Schuepp et al. (1990), where the flux (FC) measured at an upwind distance (x) from the mast can be estimated for neutral atmospheric stability as:

$$FC_x = \frac{u}{u_*}\frac{z_m}{kx^2}e^{-(u/u_*)(z_m/kx)} \qquad (2)$$

where u is the mean wind speed, z_m is the sensor height, u_* is the friction velocity and k is von Karman constant (0.4). Integrating Eqn 2, the percentage of the accumulated flux at a given distance upwind from the sensor can be found. The crosswind sector for the footprint was found using a dispersion algorithm presented by Gryning et al. (1987).

Giving the source strength at any point ($F_{x,y}$) upwind from the measuring location, the concentration is given by:

$$F_{x,y} = \frac{FC_x}{\sqrt{2\pi}\sigma_y} e^{-(y^2 / 2\sigma_y^2)} \qquad (3)$$

where y is the distance from the mean wind-axis, σ_y is the across wind spread.

The footprint model described in Eqn 2 and Eqn 3 was successfully applied in a GIS (Geographical Information System) environment by Soegaard *et al.* (2003).

We used the scaling approach suggested by Roulet (1994) that assigns the CO_2 exchange from a well-defined cover type with the area from the cover type. For each day of chamber measurements (Table 3) the 85% coverage footprint was calculated for the period 10:00 to 16:00 hours. The footprint areas were aggregated for the week (Table 3) to cover the time span of the chamber measurements. Subsequently we obtained a contributing source area for each week of chamber flux measurements. The daily eddy covariance tower footprint between 10:00 and 16:00 hours was derived using the footprint model, as presented in Eqn 3. The footprint was derived on days when measurements at the plot sites were conducted (Table 3). The spatial integrated fluxes were obtained from the weekly averaged plot site fluxes for each of the five vegetation types, weighted according to the area from the footprint of the eddy covariance tower.

Fluxes were scaled as follows:

$$FC_{Landscape} = a*(FC_{Cassiope}) + b*(FC_{Salix}) + c*(FC_{Fen}) + d*(FC_{Grassland}) + e*(FC_{Dryas}) \qquad (4)$$

where a-e is the integrated areal coverage of each vegetation type, derived from the vegetation classification, for weighting the fluxes.

Vegetation distribution map and satellite imagery

The vegetation map was based on a hyperspectral image from 8 August 2000 that was classified using maximum likelihood classification. A total of eight classes were selected from a priori knowledge of the surface type composition in the area (Bay, 1998). Hereof five vegetation classes covering more than 70% of the area were selected to represent the sites in which the chambers were located. A detailed map was produced with a resolution of 5 by 5 meters. In total five Landsat ETM+ scenes covering the period of measurements (18 June, 25 June, 4 July, 11 July and 29 July) were obtained and atmospherically corrected and NDVI was derived. Due to an instrument malfunctioning onboard the sensor (SLC-off), the images acquired had stripes with no-values. However, the stripes were the only area affected by the signal disturbance, therefore we found that the images were applicable for analysis. In order to be able to use the NDVI derived from the satellites in spite of the striping, gap filling of the no-value pixels was necessary. Hence, we averaged NDVI for each of the satellite images by vegetation type as derived from the vegetation classification for an area 500m in radius from the eddy covariance tower.

During the timespan covered by the images, NDVI increased as seen from Fig. 2. Therefore, a procedure was established to ensure satellite derived NDVI to increase as the season progressed thus NDVI0618 < NDVI 0625 < NDVI 0704 < NDVI0711 < NDVI0729. Pixels not fulfilling this criterion were also gap filled with NDVI value averaged by vegetation type. The relation between NDVI and NEE was used to derive NEE from the five satellite images. On the dates of the satellite overpass at 13:00 hours local time, NEE from the eddy covariance tower was derived in the time-interval between 10:00 and 16:00.

Results

Environmental conditions

Measurements of meteorological variables have been conducted in Zackenberg continuously since June 1996. An average has been calculated for this period for the meteorological variables, air temperature and precipitation (Table 1). The 2004 growing season was characterised by early snowmelt, by 14 June (DOY 166) the snow had melted. There were however a few snow patches persisting until 25 June (DOY 177). Compared to the previous years as reported in Groendahl *et al.* (in press), this is the earliest recorded day of snow-free at the heath site since 1997.

The precipitation during June, July and August were less than the average period from 1996-2003 (Table 1). Precipitation occurred on average every third day, however the frequency was highest during the period from 19 July until 6 August (DOY 201 – 219). Air temperatures during June, July and August were higher than during the average period.

Vegetation classification accuracy

The overall accuracy of the vegetation classification was 82.49% and the kappa-coefficient was 0.79 (Table 4). As the kappa-coefficient is used as means of classifying the agreement, the result indicates a good separation between the classes in the classification. *Dryas* heath was the only vegetation type, which was poorly classified, mainly due to the misclassification as abrasion but also confusion with *Salix* snowbed vegetation types occurred. The *Cassiope* heath vegetation type was however classified 100% correct. The accuracy test is acceptable and within the range found in similar studies (e.g. Virtanen et al. (2004)), where overall accuracy was 84% and kappa was 0.75.

Carbon exchange at plot-level

From Fig. 2, the large variation in carbon exchange in the five dominating vegetation types is clearly seen. The error bars reported here are the standard deviations from the mean value and represent the spatial variability between plots and within the vegetation types in the valley. The vegetation types can be divided into three groups of sequestration. The *Salix* and *Cassiope* dominated plots loose carbon until week 2 and 3 respectively. By week 5 the maximum uptake is found in the *Cassiope* dominated plots with an average uptake of 286 mgCO_2 m^{-2} h^{-1}, contrasted by an uptake of 392 mgCO_2 m^{-2} h^{-1} in the *Salix* dominated plots. During the entire season, *Dryas* and grassland dominated plots had a net uptake of carbon. The maximum uptakes of carbon in these two vegetation types were found in week 4, where the sink strength was 466 mgCO_2 m^{-2} h^{-1} and 337mgCO_2 m^{-2} h^{-1} respectively. The very productive fen sites acted as a strong sink throughout the nine weeks, peaking at week 7 with an average uptake of 916 mgCO_2 m^{-2} h^{-1}. Net CO_2 exchange at the fen sites showed large standard deviations that might be explained by the difference in vegetation coverage at the plots. Also the wetness of the plots explains the variability in uptake; the wetter plots had greater inputs of CO_2 during the course of the season. By August all five vegetation types began to show physical signs of senescence (deciduous leafs yellowing) and fluxes decreased, while standard deviations however seemed to maintain their size.

Carbon exchange at field -level

As seen from Table 2 the area close to the eddy covariance tower is largely dominated by *Cassiope* and *Salix*. When moving further away from the eddy covariance tower, other vegetation types increase in coverage, especially grassland (Table 2). During the first part of the period, the uptake of CO_2 increased daily and after 19 July (DOY 201) the daily exchange of CO_2 varied considerably (Fig. 3).

In Fig. 4, the daytime weekly NEE averages from the eddy covariance tower are presented. The weekly values represent the CO_2 exchange from 10.00 hours to 16.00 hours for the days of chamber measurements during a week (Table 3). Maximum uptake occurred in mid-July with an average of 261 mgCO_2 m^{-2} h^{-1} coinciding with high temperatures this month (Fig. 4). In the period from 23 June until 18 August (DOY 175 to 231) where measurements at the plot sites were performed, the daytime (10:00 – 16:00 hours) fluxes measured at the eddy covariance tower fluctuated highly from a net loss of 120 mgCO_2 m^{-2} h^{-1} to a net gain of 190 mgCO_2 m^{-2} h^{-1}, due to changes in weather conditions. From mid July more unstable weather dominated the area. During the nine weeks the eddy covariance tower monitored a net sink of CO_2 at the heath site although the error bars indicates that the first week had a few occasions of net losses of CO_2.

Spatial integration of CO_2 fluxes

The measured fluxes at plot-level were upscaled to field-level using the satellite based vegetation classification data and the modelled footprint for each week. Areal integration of the fluxes showed that in the first week the ecosystem in the footprint lost carbon (Fig. 5), while the integrated values from the eddy covariance tower showed a net gain (Fig. 4). As the season progressed the gain increased and the spatially integrated CO_2 exchange at the chambers was similar to the measured CO_2 exchange at the eddy covariance tower.

A linear regression of the weekly estimated NEE from chambers using the footprint model with the measured NEE at the eddy covariance tower showed that the footprint modelled NEE accounted for 81% (n=9, t-test, p<0.001) of the variation in the NEE measured by the eddy covariance tower (Fig. 6).

Relating CO_2 exchange to a spectral vegetation index

An objective of our research is to determine whether a relationship between CO_2 fluxes and spectral vegetation index could be established for the Zackenberg research area for measurements at plot-level. The concurrent measures of NEE and NDVI were performed from early August until the middle of August, hence measurements from the beginning of the season are lacking, which reduced the sample size (n=40).

As seen from Fig. 2 the evergreen and winter green vegetation types, i.e. *Cassiope* heath and *Dryas* heath, had very little variation in NDVI during the period of measurements. Whereas *Salix* snowbed, Grassland and Fen has more pronounced variation in NDVI, with Fen as the most outstanding, reaching peak values of approximately 0.8 by the end of July and the beginning of August. By the end of the season none of the NDVI values had decreased to the level measured at the beginning of the season, indicating that senescence had not completed by late August.

The relationship between measured canopy reflectance, and NEE is seen from Fig. 7. Although the sample size was small, the wide variety of vegetation types represented the span in NDVI as seen from Fig. 2 and the derived regression model was significant (p<0.001).

Scaling fluxes from plot- level and field-level to landscape-level

Scaling the measured NEE at field-level from the eddy covariance tower to landscape-level, as represented by the satellite images was performed using the derived regression model based on the measurements of NEE and NDVI from the vegetation plots. The comparison of the satellite derived NEE in the footprint of the eddy covariance mast and the eddy covariance tower derived flux is shown in Fig. 8. On 4 and 11 July the eddy covariance tower measured an uptake of 296 $mgCO_2\ m^{-2}\ h^{-1}$ and 304 $mgCO_2\ m^{-2}\ h^{-1}$ (between 10:00 and 16:00 hours) respectively, whereas the satellite derived NEE showed an uptake of 107 $mgCO_2\ m^{-2}\ h^{-1}$ and 127 $mgCO_2\ m^{-2}\ h^{-1}$. Contrasting these values on 18 June and 25 June the eddy covariance tower measured a loss of 4 $mgCO_2\ m^{-2}\ h^{-1}$ and a gain of 28 $mgCO_2\ m^{-2}\ h^{-1}$ respectively, satellite derived NEE estimated losses of CO_2 of was 32 $mgCO_2\ m^{-2}\ h^{-1}$ and 10 $mgCO_2\ m^{-2}\ h^{-1}$. However, on 29 July the eddy covariance tower measured a net uptake of 153 $mgCO_2\ m^{-2}\ h^{-1}$, which was matched by the satellite estimated uptake of 133 $mgCO_2\ m^{-2}\ h^{-1}$. A 5 km^2 area covering the vegetation plots was extracted from the satellite images during the nine week period, i.e. 25 June, 4 July, 11 July and 29 July and the derived linear regression model on NEE and NDVI from the vegetation plots was applied to the images. Not surprisingly, the satellite derived NEE on 25 June did not fit the area integrated NEE from the vegetation map, simply because the regression model is not robust enough at the beginning of the season. However, the derived NEE using area weighting of the plot-level fluxes (Eqn 4) agreed overall with the satellite image derived NEE for the 5 km^2 area, as seen from Fig. 9.

Discussion

Scaling fluxes from plot-level to field-level

The information gained from the eddy covariance and chamber methods is complementary and essential in understanding the spatial and temporal pattern of the CO_2 fluxes. The two methods have differing spatial and temporal scales of measurements. The eddy covariance tower measures NEE over a hectare area providing a temporal record for a 30-minute interval continuously. However, the method does not distinguish between the contributions from the vegetation types. Therefore, a footprint model which has previously improved the information gained from the eddy covariance method (Hope *et al.*, 1995; Soegaard *et al.*, 2000; Soegaard *et al.*, 2003) was applied. The chamber method quantifies NEE from a 0.038 m^2 plot for a limited time interval. All measured fluxes at plot-level showed large spatial and temporal variability between the individual plots (Fig. 2), with standard deviation indicating the spatial variability.

Upscaling fluxes to landscape level by assigning fluxes to well defined land cover classes requires high resolution information. In the Arctic region, vegetation distribution is often patchy and strongly dependent upon micro-scale differences in slope, aspect and drainage. The large difference, up to 3 fold at the peak of the growing season, in CO_2 exchange rate between the vegetation types (Fig. 2) might lead to large errors if the classification is not correct. In this study we used a high resolution vegetation map (5 by 5m) and the results from the scaling procedure indicate that the scaling procedure worked well especially during the weeks 4 to 8, where the vegetation was fully developed (Fig. 6). The *Cassiope* and *Salix* dominated plots exert the strongest control on the fluxes when scaling from plot-level to field-level (Table 2). This is especially evident at the beginning of the season, when the vegetation in the plots had not developed, resulting in lower NEE from the spatially integrated plot-level sites compared to the measured NEE at the eddy covariance tower. Thus, the eddy covariance derived field-level flux and the footprint scaled plot-level flux were oppositely directed in the first week, in the second week the eddy covariance derived flux was approximately 40 fold the flux derived from the chamber plots (Fig. 6). However as the season progressed and the vegetation developed, the footprint scaled plot-level fluxes fitted the measured eddy covariance fluxes, although the footprint scaled fluxes were generally lower. Similarly, systematic differences between fluxes measured at eddy covariance tower and chambers have previously been reported from a study conducted in Alaska (Oechel *et al.*, 1998), which indicates that the differences in scales between tower and chamber are important when scaling the fluxes from plot-level to field-level and landscape-level.

On this small scale represented by the chamber method, the vegetation is very patchy and does not develop uniformly over the growing season as seen by the large standard deviations in Fig. 2. Consequently, we speculate that increased chamber area probably will improve the results, simply because fluxes from a larger area might depict the CO_2 exchange pattern from the ecosystems more accurately. Increasing replication of sites might also improve the ability to characterise ecosystem fluxes. Thirdly, measurements covering a larger timespan during the day would probably also improve the comparability of the two methods.

NEE - NDVI relationship.

Our results showed a good correlation between simultaneous measurements of NEE and NDVI at the five different vegetation types. As seen from Fig. 7, NDVI explained 65% of the variability in NEE, therefore additional factors affect the magnitude of

NEE during the growing season (e.g. air temperature and PAR) (McMichael *et al.*, 1999). Especially temperature has previously been shown to control the primary production in High Arctic Greenland, both on a daily basis as seen from Soegaard & Nordstroem (1999) and a seasonal basis (Groendahl *et al.*, in press). As measurements were conducted during the time span at around noon, we expect that the regression model represent maximum NEE. The NDVI values measured in the five vegetation types are within the range of the reported NDVI values from Arctic tundra communities in Alaska (Whiting *et al.*, 1992; Whiting, 1994; McMichael *et al.*, 1999). An obvious constraint on the ability to apply the regression model (Fig. 7) in scaling from plot-level measurements to the satellite images is the fact that concurrent measures of NEE and NDVI were restricted to August. However, comparing with NDVI from the five vegetation types as seen from Fig. 2, we found that the span of the NDVI values in the area were captured by the regression model and we therefore find it applicable for estimating the ecosystem flux at landscape-level using the satellite images.

We imposed the regression model on the obtained satellite images during the nine week period, for a 5 km^2 area covering the positions of the vegetation type plots. In Fig. 9 the resulting fluxes from the scaling procedure from plot-level to landscape-level is seen. The scaling procedure had a satisfactorily overall agreement, only the satellite image from 25 June does not agree with the area integrated flux in week 1. This is not surprisingly, since the regression model does not include NDVI values from this early part of the season, and in addition the vegetation coverage at this early part of the season is very sparse.

When scaling NEE measured at field-level to landscape-level using the footprint of the eddy covariance tower, the NEE-NDVI regression model resulted in slight underestimations when comparing satellite image derived NEE with NEE from the eddy covariance tower (Fig. 8). Day-to-day variability in the NEE is not captured by the satellite images; consequently it would be reasonable to compare satellite derived NEE with an average of eddy covariance tower derived NEE for more than a one day measurement. The NDVI does not change rapidly (Fig. 2) and we therefore assumed that NDVI would be the same a few days before the satellite pass. The additional scatter plot on the NDVI derived NEE and the eddy covariance tower derived flux as an average of 3-days in the period of the satellite pass is also shown in Fig. 8. Using the 3-days averages of eddy covariance tower derived NEE improves the correlation and the R^2-value increases from 0.76 to 0.88. Comparing the day-time values from the eddy covariance tower with the satellite derived fluxes, revealed that the model is not robust enough at the beginning of the season, where satellite derived NEE was underestimate. A plausible explanation is the size of the footprint from the eddy covariance tower; being dominated by *Cassiope* heath and *Salix* snowbed vegetation types (Table 2), and having an area ranging from 13100 m^2 to 122500 m^2, which is only covering approximately 15 to 136 pixels at the Landsat scene, the regression model does not describe this small area adequately as it comprises five vegetation types. Secondly, the regression model only included the NEE-NDVI relationship from the peak of the growing season to the latter part of the growing season. Therefore, NEE and NDVI values from the beginning of the season are not represented. Thirdly, the spatial scale of the pixels from the satellite image affects the results due to the fact that the NDVI derived from the satellite image is based on pixels of 30 by 30 meters, and the regression model from the measured relation between the two factors is applicable for an area of 0.038 m^2. Consequently, lack of spatial resolution in the Landsat ETM pixels result in NDVI values that are averages of several vegetation types and in addition while the vegetation is developing the underlying soil will affect the radiance captured at the satellite. However scaling the NEE using NDVI derived from the satellite image resulted in good agreement during the time of the season when the vegetation had developed. Consequently, monitoring the carbon dioxide exchange in the High Arctic regions by satellite imagery would benefit from inclusion images with high spatial resolution.

Ecosystem carbon balance

Area weighting the chamber measurements within the 5 km^2 area, the area constituted a day-time seasonal sink during the nine weeks of 166 $\pm$ 141.4 $mgCO_2\ m^{-2}\ h^{-1}$ (Fig. 9). This is slightly higher than the reported seasonal values from Soegaard *et al.* (2000) and Christensen *et al.* (2000). A plausible explanation for the higher seasonal uptake this summer can be the high temperatures observed during the season (Table 1). Integrating the daily NEE values over the entire season (June - August) at the eddy covariance tower, the Cassiope heath ecosystem has a cumulative net gain of 83.9 $gCO_2\ m^{-2}$. This is comparable with the cumulative NEE the previous year, and one of the highest measured seasonal sums during the five years of consecutive measurements from the dry heath ecosystem (Groendahl *et al.*, in press). Comparing this result with other High Arctic sites, the results from Svalbard where the dry ecosystem shifted from being a net summer sink of 14.7 $gCO_2\ m^{-2}$ to a net source of 18.3 $gCO_2\ m^{-2}$ from one summer the next, seem as a strong contrast (Lloyd, 2001). The high uptake of CO_2 during a summer with higher than average temperatures, is further supported by the findings of Welker *et al.* (2004), who found increased growing season uptake of CO_2 in a dry heath ecosystem as temperature increase. By contrast, they also found that in the wet tundra ecosystem increased temperatures reduced growing season NEE. This is however not supported by the findings of Rennermalm *et al.* (2005) in the Zackenberg fen ecosystems. They found that the dry and warm growing season was also the season with the strongest sink strength on the ecosystem. Contrary to the cumulative NEE from the dry ecosystem, the fen site in the Zackenberg area had a maximum reported cumulative flux ranging between an uptake of 183 $gCO_2\,m^{-2}$ to an uptake of 450 $gCO_2\,m^{-2}$ (Rennermalm *et al.*, 2005) from these results it becomes clear that there is a large variability between the ecosystem types in the research area.

Length of the growing season is another factor that explains the sink strength in the Zackenberg research area. In growing seasons with early abatement of snow cover and rapidly increasing temperatures, the canopy development and photosynthesis is facilitated and hence the uptake of CO_2 (Groendahl *et al.*, in press).

As the High Arctic is dominated by dry ecosystems (Bliss & Matveyeva, 1992) these are highly important for evaluation of seasonal C balances. Studies performed on the dry heath ecosystem in Zackenberg have shown variable results. While measurements at the *Cassiope* dominated heath during two consecutive seasons showed net losses of CO_2 (L. Illeris, unpublished data), the heath showed net gains of CO_2 in other seasons (Christensen *et al.*, 2000; Soegaard *et al.*, 2000; Groendahl *et al.*, in press). The magnitude of the NEE in this study conducted in the *Cassiope* dominated plots however are in correspondence with previous findings in the area (Christensen *et al.*, 2000), although the timing of the ecosystem uptake has been increasingly earlier compared to the measurements from the late 1990. The plausible explanation for this is ascribed to the timing of snowmelt, which has been gradually earlier during the recent years (Groendahl *et al.*, in press).

Whether the valley is a net source or a sink on an annual basis is not predictable, since we lack measurements from the autumn and winter. An estimate on the annual flux was proposed by Soegaard *et al.* (2000) indicating that the Zackenberg area on an annual basis was a small sink of 8.4 gCO_2 m^{-2} y^{-1}. In a climate change perspective this emphasises the importance of wintertime measurements from the High Arctic as winter effluxes of CO_2 may be large (Zimov *et al.*, 1996; Oechel *et al.*, 1997; Grogan *et al.*, 2001) and the winter period has considerable longer duration than summer.

Conclusion

We have tested the capability of a simple regression model to monitor the CO_2 exchange during the growing season.

As our model explained 65% of the variability in NEE-NDVI, the NDVI approach suffers from the fact that the primary production in High Arctic Greenland is also controlled by other variables. Therefore it would be recommended to consider including other variables in the model, e.g. temperature which have previously been shown to control the variability in NEE.

Our results indicates a clear correspondence between the measurements of NEE conducted with the eddy covariance technique and the chamber technique, however there is a tendency that the footprint scaled measurements from the chambers were lower than the measured fluxes at the eddy covariance tower. This difference might be compensated by increasing the size of the chamber areas to 0.5 - 1m^2.

Using satellite images to upscale NEE showed that there is a discrepancy between the two methods, when comparing NEE from the eddy covariance method and the derived NEE from the satellite image. However when deriving NEE for a larger area (5 km^2) we showed that area weighted NEE from the chambers and the satellite derived NEE corresponds satisfactorily. Hence, satellite images are reliable products when deriving NEE from this particular High Arctic ecosystem.

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Table 1. Temperature and precipitation for the 2004 growing season and the average period 1996-2003

	average air temperature (°C)		
	June	July	August
2004	2.5	7.2	5.6
1996-2003	1.9	5.5	4.8
	Summarised precipitation (mm)		
	June	July	August
2004	3.1	10.1	3.6
1996-2003	6.9	15.5	13.6

Table 2. Areal coverage (%) of each vegetation type in the classification at 3 distances from the eddy covariance tower

		Distance from mast			**Chamber upland**
Vegetation type	**Dominant species**	**200 m**	**500 m**	**1000 m**	**5 km^2**
Cassiope heath	*Cassiope tetragona*, *Dryas octopetala x integrifolia*, *Salix arctica*, *Vaccinium uliginosum*	50.7	24.7	24.9	18.0
Dryas heath	*Dryas octopetala x integrifolia*, *Polygonum viviparum*, *Salix arctica*	0.0	1.9	1.2	0.6
Fen	*Eriophorum scheuchzeri*, *Dupontial psilosantha*	0.9	1.3	7.3	8.6
Grassland	*Arctagrostris latifolia*, *Carex bigelowii*, *Eriophorum triste*, *Salix arctica*	14.2	24.2	21.0	37.9
Salix snowbed	*Salix arctica*	34.2	35.8	30.5	26.3
Abrasion			5.0	6.5	3.3
Riverbed			7.1	8.4	1.5
Lake			0.1	0.1	0.04

Table 3. Day of Year (DOY) with measurement at the plot sites for the nine weeks field measurements

	Week								
	1	2	3	4	5	6	7	8	9
DOY	175	180	187	194	200	211	216	222	229
	176	183	188	195	205	212	219	223	230
	177	184	189	197	206	215	220	224	231
	178	186	190	198	207	216	221	225	232
				199				226	

Table 4. Accuracy assessment of the classification of the hyperspectral image obtained 8 August 2000. Overall accuracy was 82.49 % and Kappa coefficient was 0.79

Class	**Fen**	**Cassiope**	**Abrasion**	**Lakes**	**Grass land**	**Dryas**	**Salix Snow**	**Riverbed**	Total
Unclassified	0.0	0.0	5.7	0.0	1.8	3.2	0.0	0.0	**1.5**
Fen	**85.1**	0.0	0.0	9.1	0.9	0.0	5.3	0.0	**13.1**
Cassiope	0.0	**100.0**	2.9	0.0	1.8	0.0	10.5	0.0	**14.6**
Abrasion	0.0	0.0	**74.3**	0.0	0.0	38.7	0.0	0.0	**11.3**
Lakes	0.0	0.0	0.0	**90.9**	0.0	0.0	0.0	0.0	**3.0**
Grassland	14.9	0.0	0.0	0.0	**90.9**	16.1	2.6	0.0	**33.7**
Dryas	0.0	0.0	5.7	0.0	0.9	**19.4**	0.0	0.0	**2.7**
SalixSnow	0.0	0.0	11.4	0.0	3.6	22.6	**81.6**	0.0	**13.7**
Riverbed	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**100.0**	**6.3**
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Figure 1

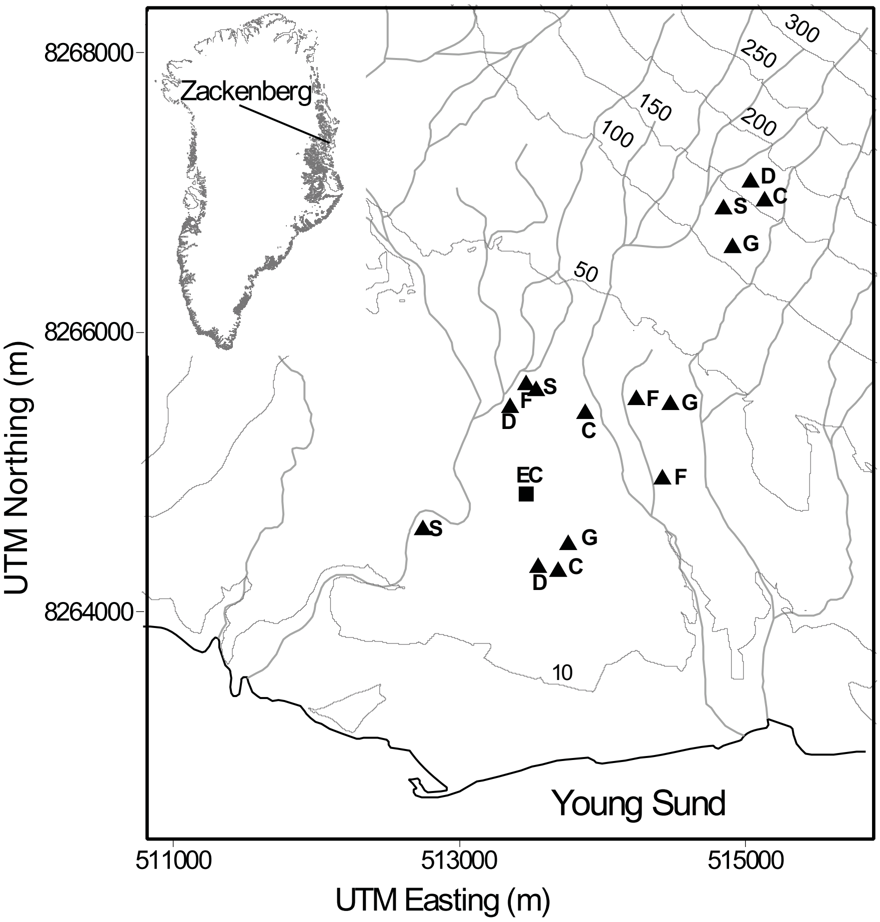

Fig. 1 Map of the Zackenberg Research area. The location of the eddy covariance mast is marked by a square, the chamber plots are marked by triangles. C= *Cassiope* heath, D =*Dryas* heath, F= Fen, G = Grassland, S = *Salix artica* snowbed.

Figure 2

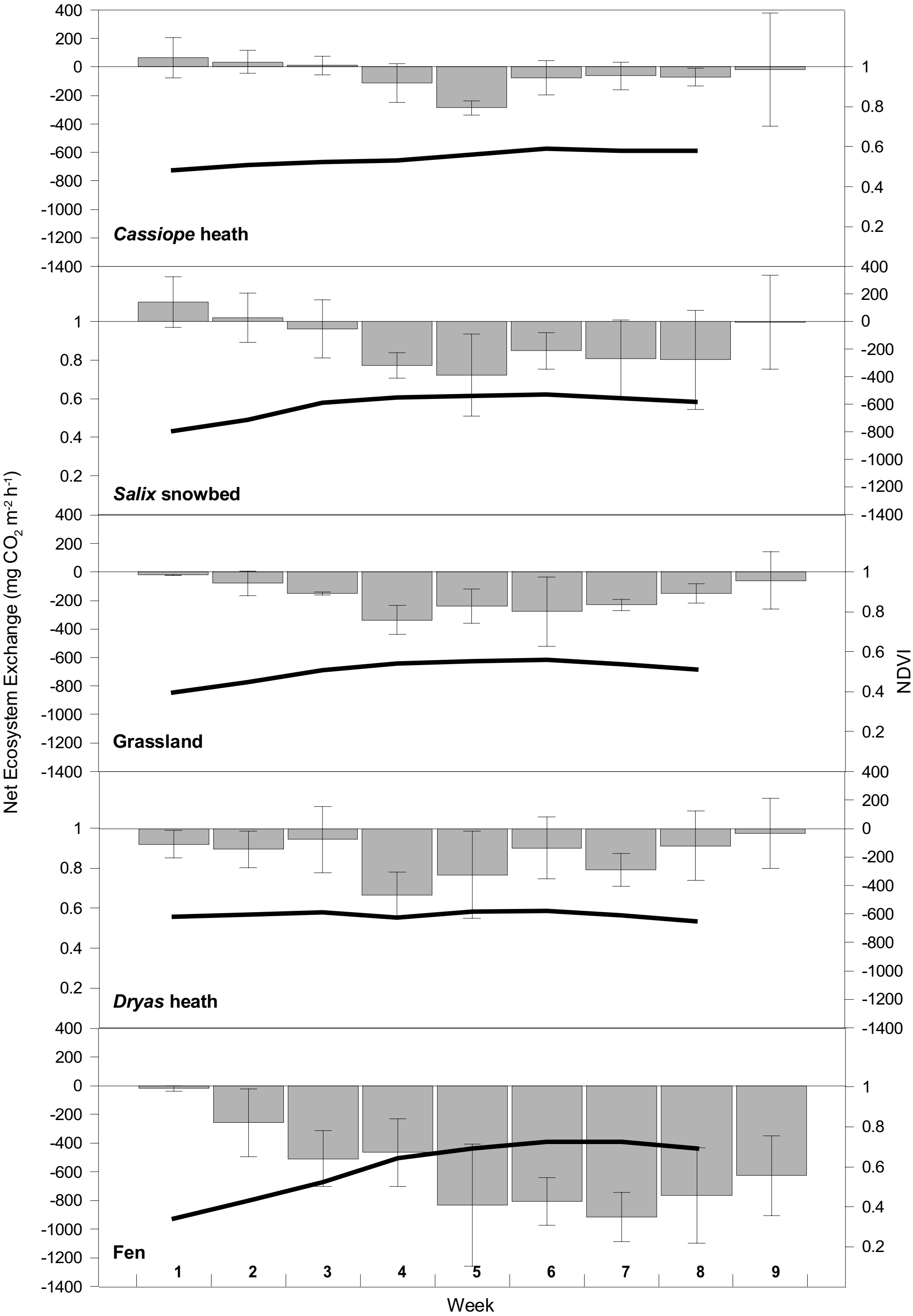

Fig. 2 Temporal variation in daytime (10:00 – 16:00 hours) average Net Ecosystem CO_2 Exchange for each community type during the nine weeks of measurements from 23 June to 19 August. From the top *Cassiope* heath, *Dryas* heath, Fen, Grassland, *Salix* snowbed. Seasonal average NDVI for each of the five vegetation types is shown. NDVI is measured at a plot next to the plot of CO_2 measurements.

Figure 3

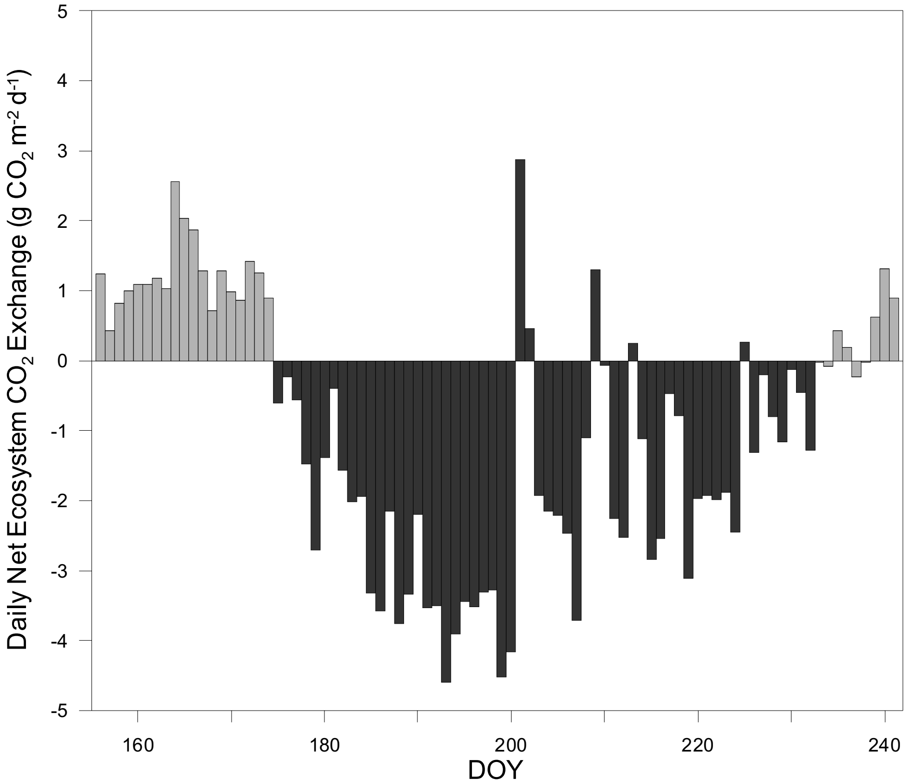

Fig. 3 Mean daily Net Ecosystem CO_2 Exchange measured at the eddy covariance tower. Dark bars represent time interval of chamber measurements.

Figure 4

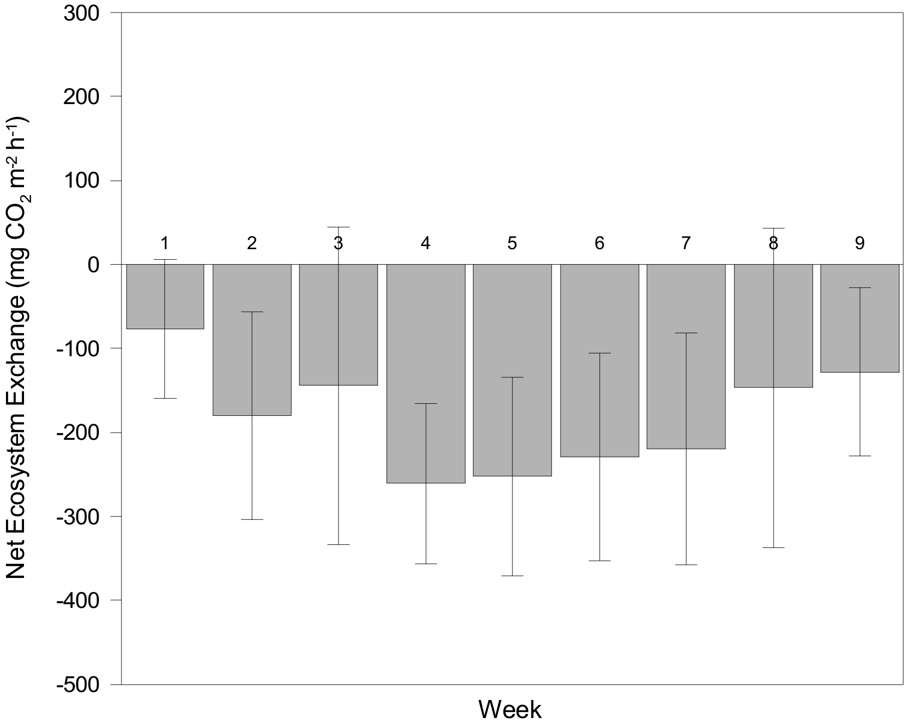

Fig. 4 Weekly daytime (10:00 – 16:00 hours) averaged Net Ecosystem CO_2 Exchange from the eddy covariance tower. Mean + SD of four or five days of measurements per week.

Figure 5

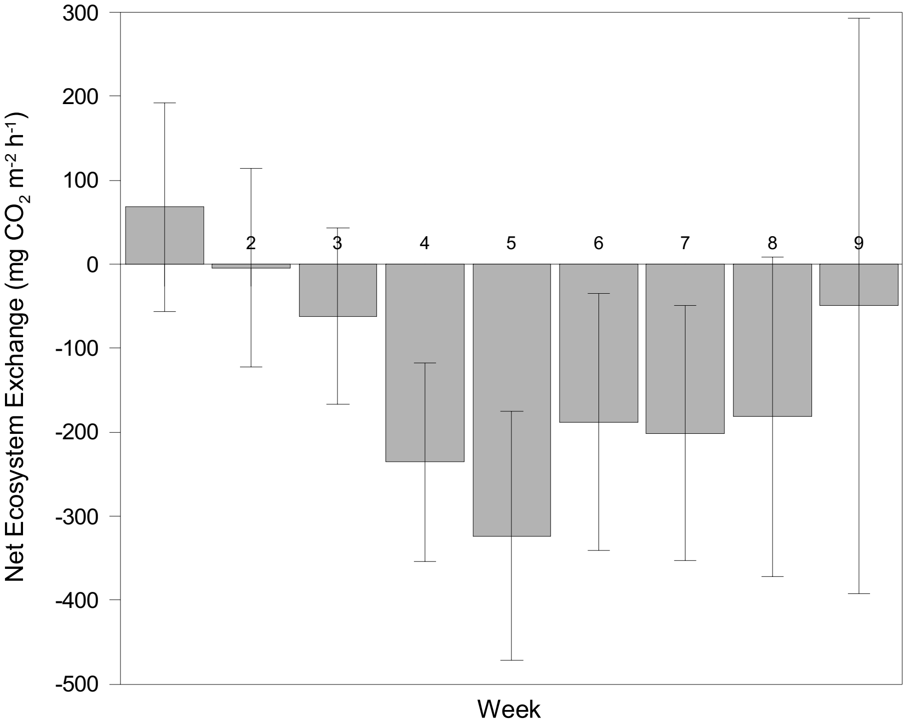

Fig. 5 Daytime (10:00-16:00 hours) chamber fluxes scaled from the weekly footprint.

Figure 6

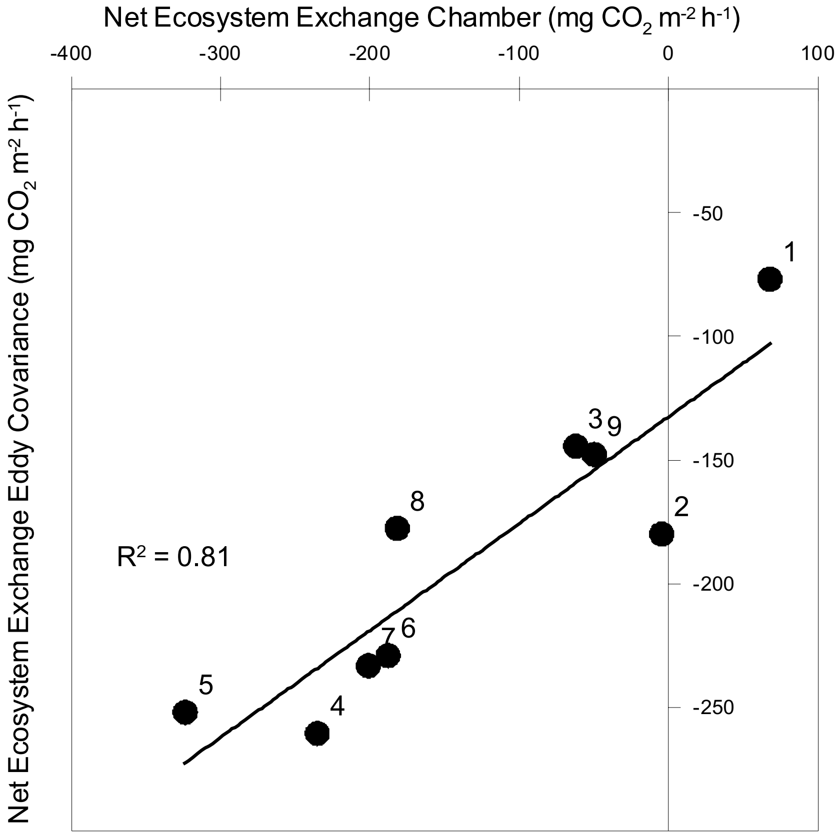

Fig. 6 Footprint scaled daytime (10:00 – 16:00 hours) Net Ecosystem CO_2 Exchange from the chambers compared to the daytime (10:00 – 16:00 hours) Net Ecosystem CO_2 Exchange from the eddy covariance tower, R^2=0.81, p<0.001. Numbers refer to week of measurement.

Figure 7

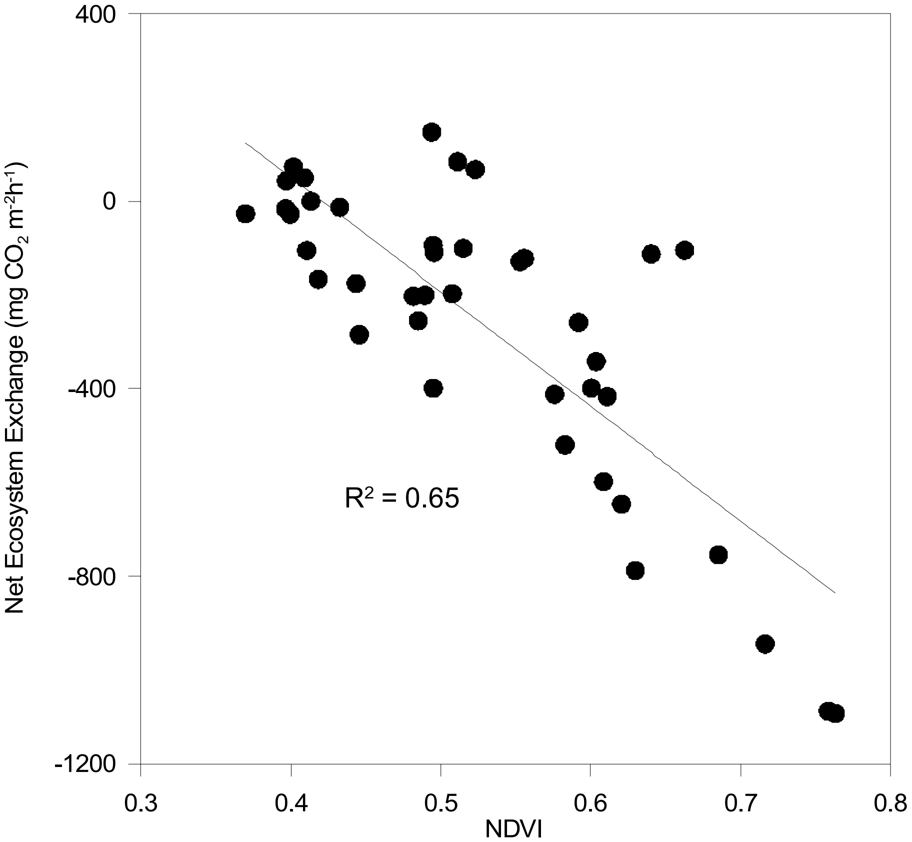

Fig. 7 Relationship between in situ measurements (community scale) of Net Ecosystem CO_2 Exchange with measurements of NDVI (Landsat ETM bands 3 and 4). NEE = -2442.1*NDVI+1027.6, R^2 =0.65, p<0.001.

Figure 8

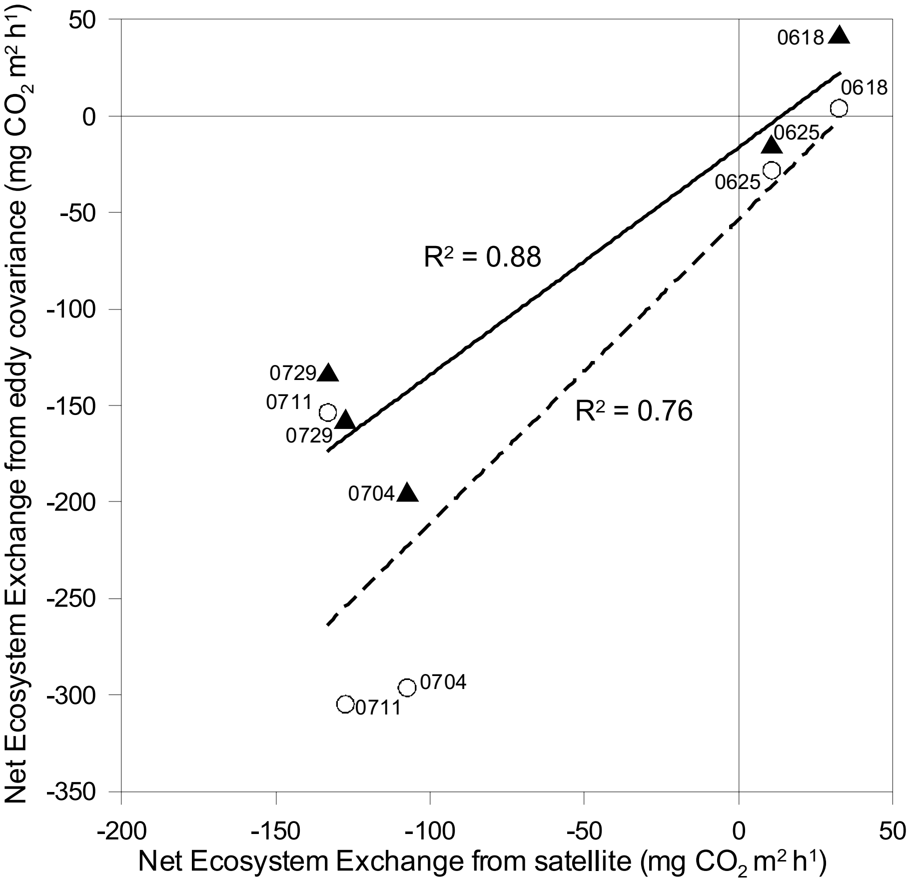

Fig. 8 Relationship between modelled Net Ecosystem CO_2 Exchange from satellite derived NDVI and measured Net Ecosystem CO_2 Exchange at the eddy covariance tower. Triangles represent the relationship between Net Ecosystem CO_2 Exchange derived from satellite and 3-days average of eddy covariance tower derived Net Ecosystem CO_2 Exchange. Open circles represent satellite derived Net Ecosystem CO_2 Exchange and eddy covariance tower Net Ecosystem CO_2 Exchange.

Figure 9

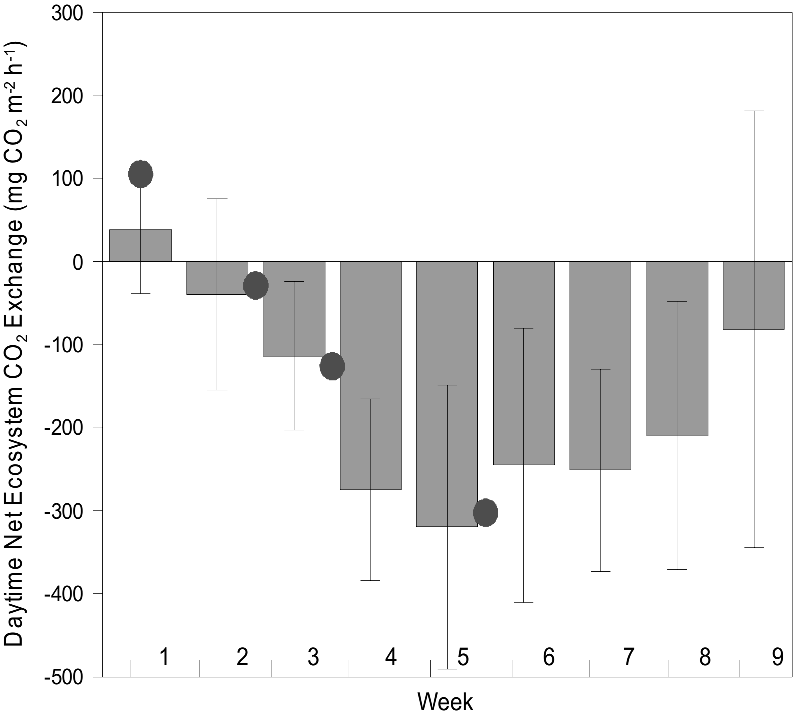

Fig. 9 Summary of the upscaled daytime (10:00 – 16:00) Net Ecosystem CO_2 Exchange for a 5 km^2 area. Upscaled chamber fluxes are weighted according to the area coverage within the 5 km^2 area, shown as bars. Satellite image derived Net Ecosystem Exchange is shown as circles.

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Paper III

Grøndahl, L. Friborg, T., Tamstorf, M., Sigsgaard, C,
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Assessing a regional carbon dioxide budget for the
growing season of a High Arctic area

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Assessing a regional growing season carbon dioxide budget for a High Arctic region

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Abstract

The estimated growing seasonal CO_2 exchange from the Arctic is usually based on a few measurements covering a small area. Remote sensing provides a tool for scaling up the fluxes and consequently to provide regional estimates of the spatial and temporal pattern in CO_2 exchange. This paper presents results from an upscaling from plot-level to regional level for a High Arctic ecosystem in NE Greenland assessed by two different methods. One estimates the regional flux by weighting the plot-level fluxes with their areal abundance and the other using an empirical model of net ecosystem CO_2 exchange (NEE) based on plot-level chamber fluxes. The model is driven by meteorological and vegetation characteristic parameters. We found that the area weighting approach in the upland areas of the region gave higher estimates of CO_2 exchange compared to the model approach, due to the altitudinal gradient in air temperature and NDVI in the area.

The region is presently functioning as a summer season sink for CO_2 with daytime average uptake rate of -102.8 ± 10.0 mg $CO_2 m^{-2} h^{-1}$, however as we do not have information from the shoulder seasons this budget is only balancing, as losses during these season are crucial to the annual budgets.

Introduction

The Arctic region plays an important role in the future climate scenarios, due to its large coverage and especially due to the large carbon stocks in the terrestrial ecosystems of the region. The slow decomposition rates in the region has led to a substantial build-up of organic carbon in the soils, resulting in approximately 14% of the Earths terrestrial stored carbon is found in the region (Oberbauer et al., 1991). The northern hemisphere have experienced a general positive temperature trend (Serreze et al., 2000) during the previous decades which seems to continue (Stendel et al.., 2006). During the same period ecosystems in the region have increased their vegetation mass (Tucker et al., 2001). Global climate models predicts annual average temperature increases of approximately 5°C for the Arctic by the end of the 21st century (IPCC, 2001), specifically with an increase in winter temperature of 6-10°C and slight increases in summer temperatures (Danish Protection Agency, 2002).
Arctic ecosystems are sensitive to climate change although the response of the individual ecosystems might differ (Chapin et al., 1997). Consequently the feedback mechanisms of the Arctic region to climate change is predicted to have a strong impact on the future climate scenarios (ACIA, 2005) and due to the large stock of carbon in the region the feedback mechanisms of this region is of particular interest in future climate scenarios.

Studies from the Arctic circumpolar North reports on a diverse sequestration pattern in the region. In Alaska the wet ecosystems have been studied intensively, indicating that the ecosystems in this area can shift from a sink to a source of CO_2 within a short time interval (Oechel et al., 1995). These ecosystems may consequently have a significant positive feedback to potential warming if ecosystem respiration continues to exceed gross photosynthesis (Oechel & Vourlitis, 1994). Similarly results from a

High Arctic polar desert locality in Svalbard provided detailed information on how the ecosystem during two consecutive summer seasons shifted from a source to a sink (Lloyd, 2001). This is however not supported by findings from NE Greenland, where increased growing season temperatures seems to increase sink activity in wet as well as dry ecosystems (Soegaard & Nordstroem, 1999; Rennermalm et al., 2005; Groendahl et al., in press). A recent estimate of the total carbon budget of the circumpolar North, suggests the regional balance is near null (Christensen et al., 2006).

To be able to reach a better understanding of the impact of climate change in a region, spatial and temporal estimates of the CO_2 exchange are needed, in particular from the High Arctic region characterised by scarcity in data availability. Access to the High Arctic is very limited apart from a few months each year which is the main reason why this region is relatively poorly documented in relation to exchange of CO_2 on an annual basis. Consequently a modelling approach enabling extrapolation of the ecosystem functionality in relation to e.g. CO_2 exchange from the few locations where data are available to cover larger areas of the Arctic region, could potentially enhance the understanding of the Arctic region in relation to a changing climate. Further regional estimates on the CO_2 exchange are lacking from the High Arctic, due to the logistical constraints on the work in the region. Consequently regional estimates from remote sensing sources are valuable tools in monitoring the CO_2 exchange on a timely and more efficient manner and complimenting the few ground based observation from eddy covariance and chamber techniques and hence to characterise source and sinks of CO_2 on regional scales. Studies have shown the capability of remotely sensed vegetation indices to provide information on key plant characteristics, e.g. plant biomass production and leaf area index (van Wijk & Williams, 2005) and additionally remote sensing provides spatially-continuous data, which can be utilised in monitoring of regional patterns of CO_2 fluxes (Whiting et al., 1992; Hope et al., 1995; Stow et al., 1998; McMichael et al., 1999).

Previously models relating CO_2 and the Normalised Difference Vegetation Index (NDVI) have been derived for Alaska (Whiting et al., 1992; McMichael et al., 1999) and recently also a linear relationship between CO_2 and NDVI has been derived for NE Greenland (Groendahl et al., in press). These models estimate carbon flux at scales consistent with chamber measurements. For a large region in Alaska, Vourlitis et al. (2003) presented a model for scaling CO_2 from plot to regional level with a minimum data approach consisting of NDVI, air temperature and radiation data layers.

A regional budget for this High Arctic region has to these authors knowledge not been assessed previously. Expanding on the work already performed in the Zackenberg region (Soegaard et al., 2000) we upscale fluxes from four vegetation types to the region using remote sensing derivable parameters; a landcover map, NDVI and additionally air temperature and radiation, to assess a regional CO_2 budget for the growing season 2004. We implement two different methods; the area weighting where fluxes are assigned to well-defined landcover vegetation types (Roulet et al., 1994) and a simple flux model (Vourlitis et al., 2003) is used for estimating fluxes based on a few input parameters. Finally we discuss the applicability of the two methods.

Methods and materials

Study area

The Zackenberg research area (74°30'N, 21°00'W) is located in the High Arctic. The valley is N-S oriented with extensive vegetation cover. The main study area in the region is an approximately 6 km wide valley bottom surrounded by mountainous terrain with several peaks reaching 1400 m, bounded by Tyrolerfjord to the south (Fig 1). Contrasting to theses altitudes the Zackenberg valley is gently sloping from 20m.a.s.l. at the coastal part of the valley up to 120m.a.s.l. at the inner part of the valley. Central in the valley the river, Zackenberg-elven, drains into the fjord. The river has a catchment area of approximately 514 km^2 of which 20% is covered by glaciers. The research area is located in the eastern part of the glaciated A.P.Olsen Land.

Minimum temperature during the coldest month ranges between -30°C and -35°C, during the warmest month maximum temperatures reach above 15°C. Average annual temperature ranges from -8.5°C to -10°C. Annual precipitation is on average 230 mm, with approximately one fourth falling as rain during the summer season.

The vegetation in the valley is composed of heath, fens, grassland and snowbed communities distributed according to topography and hydrology. The areal distribution of the ecosystems in the intensively classified region (C. Bay 1998) is seen from Table 1. This distribution is representative of the area. The heath communities are typically composed of *Cassiope tetragona* and *Dryas octopelata/integrifolia* as dominating species. *Cassiope tetragona* dominated communities are typically found in the lowlands whereas *Dryas* sp. dominated heaths are found in the lowlands but more frequently on the higher mountain slopes. Fens characterised by non-patterned hummocky terrain are found in the lowlands on level terrain with wet soils dominated by *Eriophorum scheuchzeri* and grasses often associated with snow banks. Grasslands are found on tussock terrain both in the lowlands and on the slopes dominated by graminoids. The snowbed communities are dominated by *Salix artica,* located in the lowlands as well as on the slopes.

Carbon dioxide flux and environmental measurements

During the growing season in 2004 measurements of Net Ecosystem Exchange (NEE) of CO_2 were conducted once a week for nine weeks. A portable flux chamber system (EGM, PP-systems) was used in the five tundra vegetation types; *Dryas* heath, *Cassiope* heath, *Salix arctica* snowbed, grassland and fen. These vegetation types cover approximately 69% of the mapped area (Bay 1998) (Table 1). In total 15 vegetation plots, three replicates for each vegetation type, were laid out in the research area extending in altitude from approximately 50m.a.s.l to 150m.a.s.l. Each of the vegetation plots had nine sub-plots of which one was used for continuous CO_2 flux measurements whereas the other eight were used for biomass determination, once per week (not included in this paper). The CO_2 fluxes were averaged to a weekly flux for each vegetation type. For each of the five vegetation types concurrent measurements of canopy reflectance in the red and near infrared bands corresponding to the channels at the Landsat ETM+ were measured at a separate plot each week and averaged to a weekly NDVI value. Additionally, eddy covariance measurements were made at a *Cassiope* dominated heath. These are used for comparison with the plot measurements. Details on the sampling procedures and data processing are found in Groendahl et al. (submitted).

Satellite image classification

Since the existing vegetation map (Bay, 1998) only covers a small part of the study area, a land cover map was derived from a supervised classification of a Landsat TM scene acquired for 10 August 1997 where the vegetation was fully developed. The image was geo-referenced and atmospherically corrected. The Landsat TM bands 1-5 and 7 were used in a maximum likelihood classification with ground-truthed target areas used for interpretations. Using the supervised classification method requires the interpreter to have some a priori knowledge of the area in the classification. Training sites for the classification were chosen from homogeneous area for which detailed vegetation descriptions were available (Bay, 1998). Four landcover classes were identified; *Cassiope* and *Dryas* dominated heath, the grasslands, the wet fen areas and the *Salix arctica* dominated heaths. These covertypes are the dominating vegetation types in the area; additionally non-vegetated areas were classified. To assess the quality of the selected training areas, the Jefferies-Matusita (J-M) separability was calculated, indicating the separability of the training areas. Satisfactorily separabilities between the landcover classes were found (J-M separability ranging between 1.9 and 2.0). Additionally a set of independent test areas were chosen to determine the accuracy of the classification. Training and test areas were all chosen within the area classified by Bay (1998). The accuracy of the classification was verified by calculating a confusion matrix, reporting the overall accuracy and the kappa coefficient.

Satellite derived NDVI

Vegetated surfaces have two distinct wavelengths determined segments of reflectance; low reflectance in the red part of the electromagnetic spectrum due to chlorophyll

absorption and a high reflectance in the near infrared part of the spectrum caused mainly by cell structure and leaf area. The difference in reflection between the two wavelengths is used in the NDVI which has been shown to be sensitive to the fraction of absorbed photosynthetically active radiation, production of biomass, leaf area, chlorophyll content and density of the vegetation (Myneni et al., 1995; Boelman et al., 2003; Zhou et al., 2003). Consequently, NDVI can be used as a surrogate for estimating seasonal ecosystem development and phenology (Markon et al., 2005).
In total six cloud-free Landsat ETM+ scenes from the 2004 growing season were obtained, geo-referenced and atmospherically corrected and used for NDVI calculations. Due to an instrument malfunctioning onboard the sensor (SLC-off), the images acquired had stripes with no-values. However, the stripes were the only area affected by the signal disturbance; therefore we found that the images were applicable for analysis. In order to obtain full coverage of NDVI from the satellite imagery in spite of the striping, gaps were corrected by filling in average NDVI values for each landcover class. The procedure is thoroughly described in Groendahl et al. (submitted).

Modelling Net Ecosystem Exchange

The Net Ecosystem Exchange (NEE) is the difference between two oppositely directed fluxes; the Gross Ecosystem Production (GEP) which is also known as the gross ecosystem photosynthesis and the ecosystem respiration (ER).

$$NEE = GEP - ER \qquad (1)$$

ER was measured directly while GEP was calculated as the difference between the also directly measured NEE and ER at the plot-level sites.

We modelled NEE by a combined representation of photosynthetic irradiance-response and temperature-sensitive respiration, using a hyperbolic function approach and an exponential model for temperature dependent respiration. Model estimation calculations were performed for each vegetation type using non-linear regression. We determined the unknown parameters for the model by the least squares regression method with the statistical software SPSS for Windows (Release 11.5. SPSS Inc., 2005).

$$GEP = \left(\frac{a_1}{1 + exp(a_2 - a_3 * NDVI)} \right) \left(\frac{a_4 * PAR * a_5}{a_4 * PAR + a_5} \right) \qquad (2)$$

where, PAR is the Photosynthetically Active Radiation obtained from the chamber measurements. NDVI was measured at the individual plots, used as a surrogate for the development in leaf area and aboveground biomass. The sigmoidal function of NDVI was suggested by Vourlitis et al. (2000) for the Kuparuk River Basin. As the NDVI in the Zackenberg area develops in a sigmoidal fashion, with an increase at the beginning of the growing season until a maximum of greenness has been reached followed by a decline in NDVI as the vegetation senescence, we found this approach suitable in the upscaling of the fluxes to a regional level, a_1-a_5 are the regression coefficients.

Soegaard et al. (2000) found that development in vegetation during the growing season had an impact on the respiration, therefore it seems reasonable to include NDVI in the estimation of ER, we have adopted the approach for this from Vourlitis et al. (2003)

$$ER = \left(\frac{b_1}{1 + exp(b_2 - b_3 * NDVI)} \right) (b_4 * exp(b_5 * T_a)) \qquad (3)$$

where, T_a is the chamber air temperature and b_1-b_5 are the regression coefficients. Although soil temperature is more commonly used as a predictor of the soil microbial activity, we used air temperature in the derivation of respiration. This parameter is widely available in the region from the meteorological towers and the aboveground plant respiratory component of ER is more closely related to variations in air temperature (Vourlitis et al., 2000).

Scaling CO_2 *fluxes from plot to regional level*

Two methods were used for scaling the plot-level fluxes to regional level. The Satellite-Model (SatModel) and the Area Weighting (AW) approach.

The SatModel applies the derived nonlinear models in Eqn 2 and Eqn. 3 for the four vegetation types, spatially scaling the CO_2 exchange to the region using a Geographical Information System (ArcGIS 9.1, ESRI). A GIS database consisting of the landcover map and dynamic layers of temperature, PAR and NDVI was established. All layers were geo-referenced and co-registered to a common pixel size of $900m^2$ (30 by 30m) corresponding to the Landsat ETM+ and Landsat TM images. Taking into account the mountainous terrain in the area the daytime (10.00-16.00 hours) PAR layers for the days of satellite overpasses were calculated by interpolating observed values from three meteorological station in the valley and correcting for elevation by calculating the skyview (i.e. the percentage of visible sky in a terrain model) for each pixel. Average daytime temperature maps were calculated using data from the three meteorological stations within the valley and adjusted for elevation and lapse rate using the MicroMet submodel in the SnowModel (Liston & Elder, 2006). Assuming that the CO_2 exchange depends on the areal coverage of the different ecosystems in the region, the AW approach uses the weekly average estimates of net

CO_2 exchange from the four landcover classes and assigns this flux to the landcover type identified on the satellite derived vegetation map, the regional flux is calculated by area weighting each landcover type (Roulet et al., 1994). This method has previously been applied in a scaling approach for larger areas (Roulet et al., 1994; Heikkinen et al., 2004).

Results

Environmental conditions

Measurements of meteorological variables have been conducted in Zackenberg continuously since June 1996. Compared to the average period 1996 – 2004 the air temperature in June, July and August 2004 was higher, the precipitation was significantly lower and the short wave incoming radiation was in the same order of magnitude as the average period (Fig 2).

The 2004 growing season was characterised by early snowmelt. At the meteorological station melting was completed by 14 June (DOY 166) although a few snow patches persisted until 25 June (DOY 177). Compared to the previous years as reported in Groendahl et al. (in press), this is the earliest recorded day of snow-free at the heath site since 1997.

Satellite image classification

A Landsat TM scene from 10 August 1997 was classified into 11 landcover classes based a priori knowledge on the distribution of the different covertypes from the previous classification performed by Bay (1998) (Table 1). On this basis satellite imagery representative (training) areas of significant landcover classes were selected, in total four vegetation classes were distinguished, defined in accordance with the chamber flux vegetation classes. The Landsat-TM has a pixel size of 30 by 30 m resolution, which is sufficient to identify major cover classes. Although the vegetation composition in the Zackenberg area is organised in rather well defined units, vegetation patches with a size less than 30 by 30 m occurs and hence, there is a risk that vegetation types covering only small areas is not classified correctly. The vegetation in the area has an altitudinal different distribution, *Dryas* dominated heath is found mostly in the upland covering small patches whereas *Cassiope* heath is mainly located in the lowlands. Consequently we decided to aggregate these two vegetation types into one heath cover class. The two vegetation types are the dominating species in the heath landcover type and moreover they have similar flux rates and NDVI. Three additional vegetation classes were identified fen, grasslands and *Salix artica* snowbed.

The Landsat TM records reflectance from seven discrete wavelengths in the visible and near infrared portion of the electromagnetic spectrum for each pixel. The maximum likelihood method was used to create a classified image by assigning each pixel one of 11 landcover classes. Training classes and ground truth classes were chosen independently, i.e. there was no overlap between the two sets of classes.

The resulting accuracy assessments showed the classification was performed satisfactorily. The overall accuracy of the classification was 83% with a kappa coefficient of 0.81. The kappa-coefficient yields a measure of the agreement between classes, the result indicates a good separation between the classes in the classification (Jensen, 1996). The classification is 81% better than a classification that resulted from random assignment. The overall accuracy is comparable with previous landcover classifications performed in the Arctic, resulting in accuracy assessments ranging from 57% (Stow et al., 1989) up to 86% (Mosbech & Hansen, 1994).

The classification result was used for determination of the areal coverage of vegetation types in the area, needed for scaling the measured CO_2 fluxes to the regional area (Table 1).

As seen from Table 2 the *Salix arctica* snowbed class was poorly classified, 39.2% was classified as grassland and 17.6% as fen. Also the grassland class was to some extent misclassified as *Salix arctica* snowbed, which indicates that the spectral reflectance from these classes is somehow similar and difficult to separate.

Net ecosystem exchange in the Zackenberg area

In Fig. 3 daytime NEE from the intensive field campaign following snowmelt from June to August is presented. Daytime NEE was measured in five vegetation types, two were however as mentioned previously, aggregated into a heath vegetation type consisting of *Cassiope* and *Dryas*. The aggregated heath vegetation types were weighted according to their relative abundance in the vegetation map by Bay (1998) consequently *Dryas* constitute 37% and *Cassiope* for 63% of the class. It is assumed that the distribution of the two types in the region is the same as within the valley area.

The composite heath vegetation type had average daytime positive NEE, indicating that there was a net uptake of CO_2. The standard deviations however indicate that there were losses of CO_2 from this composite vegetation types during the growing season. From the beginning of the nine-week period, small uptake of CO_2 were measured and by week five daytime peak uptakes were 300.2 $mgCO_2\,m^{-2}h^{-1}$. In contrast grassland and *Salix arctica* snowbed vegetation types lost CO_2 to the atmosphere (positive values denoting loss of CO_2 to the atmosphere) at the beginning of the season. However as the vegetation developed the uptake rates increased and maximum average daytime uptake reached 391.7 $mgCO_2\,m^{-2}h^{-1}$ in the *Salix arctica* snowbed vegetation type. The fen acted as strong sink throughout the nine-week period with a seasonal peak uptake rate of 916.3 $mgCO_2\,m^{-2}h^{-1}$ by the end of June. The seasonal peak for the fen was later than for the three other vegetation types, due to later development of the vegetation and hence later peak of NDVI.

Modelling and upscaling CO_2 fluxes to regional level

Figure 4 shows the modelled values from Eqn. 2 and 3 of GEP and ER plotted against the measured fluxes. Some scattering around the 1:1 line is seen for ER and the R^2 of 0.7 indicates that the fit is not perfect. The discrepancies in ER between modelled and measured results are related to ER from the fen sites where two occasions of low temperatures in June and August resulted in lower modelled fluxes compared to the measured fluxes. The modelling of GEP showed a good agreement between model and measured GEP as indicated by centring on the 1:1 line and R^2 of 0.94. Using the parameterisation of GEP and ER to derive NEE (Eqn. 1) showed a reasonable agreement, with 88% of the variance in the modelled flux explained by the measured flux throughout the nine week season.

In Fig. 5 the growing seasonal development in NEE derived using the SatModel approach is seen. A general increase in NEE is seen throughout the growing season from 18. June 2004 to 29 July 2004, hereafter the uptake rates decreases. On 18 June (DOY 170) daytime losses were up to 300 mg $CO_2m^{-2}h^{-1}$, however the majority of the pixels exhibited losses ranging from 0 to 50 mg $CO_2m^{-2}h^{-1}$. One week later on 25 June (DOY 177) GEP exceeded ER and accumulation occurred in parts of the lowland areas. The sink activity increased as the season progresses and by 29 July (DOY 211) when the vegetation was fully developed uptake rates in the fen reached up to 859.3 mg $CO_2m^{-2}h^{-1}$. The resulting NEE on the satellite image from 30 August (DOY 243) indicates that ER at this time exceeds GEP causing the ecosystem to loose CO_2 to the atmosphere. The fen vegetation types did however on average show uptake of CO_2 even at this part of the season.

Not surprisingly the lowest fluxes are found in the upland area, as the vegetation is more sparsely represented by increasing altitude resulting in a likewise decrease in NDVI. Moving from East to West in the region, the altitude increases. The vegetation is distributed in the valleys of the region, consequently the frequency of vegetation in the valleys with altitudes of approximately 300m is as dense as the vegetation in the Zackenberg valley. This phenomena is quite unique for this region, as vegetation normally in the high Artic is found below 200-300m.a.sl. (Bay, 1998). In Greenland the greatest luxuriance in vegetation is encountered from 300-600m a.s.l. (Fredskild, 1998). The approximate limit of vegetation in the region is extending up to an elevation of 550 m (Bay & Boertmann, 1988). Vegetation above this limit usually is dominated by mosses (B.U.Hansen pers. comm.) and therefore results in erroneously high NDVI value. Consequently there is only a slight reduction in NEE, in the upland areas compared to the Zackenberg valley. In the upscaling only areas classified up to an elevation of 550m is included. As no measurements were performed on the barren surfaces and the limnic systems in the area, these were not included.

The SatModel derived area integrated average daytime NEE for the individual vegetation types, is seen in Fig 6a. Large differences is observed between the four vegetation types, especially the *Salix arctica* snowbed vegetation type looses CO_2 to the atmosphere at the beginning of the season. The average daytime area integrated NEE derived with the SatModel were comparable to the AW fluxes for most of the growing season, the AW fluxes were however considerable higher on 11 July (DOY 193) and 29 July (DOY 211) 2004 (Fig 6b), due to a period of high temperatures.

The resulting average daytime CO_2 flux from the individual vegetation types assessed with the SatModel procedure and the AW procedure was bootstrapped, a total of 1000 data series were constructed by resampling with replacement the daytime average CO_2

flux for each vegetation type, and the seasonal mean and standard errors were calculated from the sample data series. In Table 3 average daytime NEE for the four vegetation types and the average exchange is seen. A comparison of the temporal integration of the SatModel and AW derived fluxes in the period from DOY 177 to DOY 231, shows some differences between the two methods. For both methods the fen areas showed strong sink activity as compared with the other vegetation types in the area, seasonal daytime mean uptake of -412.6 ± 22.7 mgCO$_2$ m^{-2}h^{-1} and -609.5 ± 32.9 respectively. Whereas the heath vegetation type had a seasonal uptake rate of -77.6 ± 4.9 mgCO$_2$ m^{-2}h^{-1} and -126.7 ± 13.2 mgCO$_2$ m^{-2}h^{-1} respectively. The fluxes derived using the SatModel approach are comparable with previous findings using the chamber method in the region (Christensen et al., 2000), except for the fen vegetation types which resulted in higher uptake rates than previously observed. Whereas the AW derived fluxes are slightly higher than previously reported findings, which might be explained by the length of the period of uptake (Fig 3).

Comparing the overall seasonal mean from the two upscaling methods (Table 3), it can be observed that area integrated mean using the SatModel approach was approximately 30% lower than the AW approach. This is due to the difference in the methods, SatModel includes the spatial and temporal development of the vegetation whereas the AW method only includes the temporal change in flux. As seen from Fig. 6a the average daytime losses during the early part of the growing season were substantial.

For comparison the average daytime NEE measured at the eddy covariance mast is given in Table 3. As seen the seasonal average of the eddy covariance measured CO$_2$ exchange is comparable to the AW seasonal averages for the heath, *Salix* and grassland vegetation types. These are the most frequent vegetation types in the footprint of the eddy covariance mast (Groendahl et al., submitted). The SatModel derived fluxes are however somewhat lower than the eddy covariance derived fluxes. In this study we have not footprint corrected the fluxes, but the magnitude of the fluxes corresponds well between the AW fluxes and the eddy covariance fluxes. Observing the difference in area integrated mean CO_2 exchange for the two methods, the difference is 2 fold when comparing the fluxes for altitudes above 300m (Table 3). This is mainly explained by the difference in vegetation density, as previously described the vegetation density decreases with increasing altitude.

Discussion

CO_2 fluxes

The plot-scale measurements conducted during the 2004 growing season, revealed that net uptake of CO_2 began early this season, and additionally the uptake rates were as previously mentioned, slightly higher during the 2004 field campaign (Fig. 3) compared to the results presented by (Christensen et al., 2000). The early start of uptake is mainly attributed to the early snowmelt observed this year (Groendahl et al., submitted). This indicates that photosynthesis probably had an early start this year and by the time the plot-level measurements began on 24 June (DOY 176), the fen was already a net sink of CO_2. By the end of the measuring period on 18 August 2004 NEE had declined in most of the vegetation types, the fen area however still had high uptake rates of -627mg CO_2 $m^{-2}h^{-1}$. This is somewhat higher than the previously reported CO_2 exchange rates (Christensen et al., 2000). A possible explanation for this high activity is probably found in the relatively high NDVI values at this time of season, whereas the other four vegetation types had decreasing NDVI, the fen area had average NDVI values of 0.64, indicating that a high proportion of photosynthetic tissue was still found in the graminoids.

In addition the air temperature was higher than during the average period, which has been seen from other studies to favour photosynthesis (Welker et al., 2004; Groendahl et al., in press), as well as to increased respiration.

Upscaling the CO_2 exchange to regional level

To understand the response of Arctic ecosystems to climate change and to assess the role of the Arctic ecosystems in the global atmospheric CO_2 budget, regional estimates of net CO_2 flux are required (Baldocchi et al., 1996). Consequently the application of simple physiologically based models for scaling plot scale measurements of CO_2 exchange represents a critical step to provide reliable estimates of large-scale CO_2 exchange (Whiting et al., 1992; McMichael et al., 1999; Oechel et al., 2000).

Satellite remote sensing provides capabilities for regional mapping and monitoring of biophysical variables for Arctic carbon cycle research and at spatial and temporal scales that are generally inaccessible or impractical to field observations (Sitch et al., 2006). Combining the exchange of CO_2 from a small area with the vegetation index provides a tool for scaling up the measured flux to a large area (Whiting, 1994; McMichael et al., 1999; Vourlitis et al., 2003).

Two very different methods are used in this study to estimate the regional CO_2 exchange over the growing season. The methods are different in their approach; AW is static and constrained to the distribution of the vegetation types in the area, whereas the SatModel although implementing a vegetation map uses the NDVI, air temperature and radiation for the temporal and spatial scaling of fluxes.

The SatModel approach used the derived models for GEP and ER for each of the vegetation types, to calculate NEE for each vegetation type. The models performed well, explaining 88% of the temporal variance in daytime NEE. The method has previously been tested in Alaska and have proven to give reliable results even on the annual basis (Oechel et al., 2000; Vourlitis et al., 2003).

The AW approach is subject to some bias as it holds an assumption the vegetation density within each vegetation type is the same, consequently the CO_2 fluxes measured in the Zackenberg valley were scaled to the regional level without taking into account that the vegetation density is decreasing as altitude increases. As seen in Fig. 3 the difference in CO_2 exchange between the vegetation types was large, during the intensive part of the growing season the difference was up to a factor of 8. Since the vegetation map is central in both methods, a correct classification of the landcover classes is therefore important when assessing a regional CO_2 budget. The estimated overall accuracy of 83% is satisfactorily compared to other landcover classifications in the Arctic. The spatial resolution is however debatable, as the image might have too coarse resolution to identify the landcover classes with low spatial extent in the image.

The AW approach in general gave higher estimates of NEE for all vegetation types compared to the SatModel approach (Table 3), although the two approaches gave almost similar exchange rates at the beginning and end of the season (Fig 6b). An altitudinal gradient is seen in the area. In the eastern part of the region the valleys are located in approximately 300m.a.s.l. whereas the valley floor in Zackenberg Valley ranges between 0 and 100m. Taking the altitudinal difference in the region into account we find that the two methods differ substantially. AW shows only slight differences between altitudes above and below 300m as it only reflects differences in vegetation composition and not in density whereas the SatModel method shows that the fluxes decrease as elevation increases as a result of changes in both vegetation composition and density. Consequently taking into account the altitudinal difference as seen in Table 3, the difference between the two methods is striking. Subsequently due to the mountainous terrain in the region the SatModel approach seems to provide more reliable estimates of the regional NEE, taking into account the difference in vegetation density, air temperature and radiation.

To obtain an estimate of the total exchange over the growing season, the 74 days covering the satellite images were integrated. The seasonal budget for the growing season suggests that the region is a daytime net consumer of CO_2 with an uptake of

-1.07 ± 0.11 Gg CO_2. The estimate is based on a spline fit of the temporal coverage, consequently the seasonal CO_2 budget should be viewed as a tentative estimate. Results on growing season NEE for High Arctic localities have been found to range from approximately a loss of approximately 14 $gCO_2\ m^{-2}$ to an uptake of -18 $gCO_2\ m^{-2}$ (Lloyd, 2001) for an Arctic desert on Svalbard to carbon budgets for the Zackenberg valley in July-August of $-68,8 \pm 24,5$ $gCO_2\ m^{-2}$ (Soegaard et al., 2000). Converting the daytime NEE to daily values the carbon budget assessed with the SatModel method is well within theses values, with growing season NEE for the areas below 300m.a.s.l. -46.4 ± 12.7 $gCO_2\ m^{-2}$ for the SatModel.

Monitoring CO_2 exchange by satellite imagery

Spatial distribution of both temperature and the areal distribution of green leaf area (e.g. LAI or the surrogate NDVI) was found by Soegaard et al. (2000) to have significant importance for the estimation of NEE. Using satellite imagery provides a means for deriving the spatially distributed parameters. Deriving vegetation maps is often limited by the spatial resolution due to the high heterogeneity of the vegetation in the Arctic tundra landscape. The Landsat ETM+ satellite provides a relatively high spatial resolution and a relatively frequent overpass in the polar region. This is however disturbed by the frequent cloud coverage in the region, preventing elaboration of high frequency timeseries of images. Consequently estimating NEE at regional scale should be done using satellite imagery with high spatial and temporal resolution.

For a verification of the scaled values found through the two methods, additional measurements for the different vegetation types are needed especially on the mountain slopes at altitudes above 150m.

It is important in a scaling procedure like this to include as many vegetation types in the upscaling model as possible to make sure that all land cover classes are represented. Using the AW scaling approach requires that the chamber measurements used are representative of the ecosystem i.e. large spatial and temporal coverage is needed in order to be sure to capture the variability in the controls on the CO_2 exchange. The SatModel scaling approach using a simple model, encounters a lot of variability in the fluxes. In this study there is however a drawback, that the measurements does not capture the shoulder season, which are extremely important in terms of carbon budgets (Christensen et al., 2006).

This call for additional chamber measurements in this area, particularly interesting are also the barren and limnic sites, which may contribute to the areal flux but has been assumed to be neutral in the present study due to lack of measurements. Additionally a soil composition map would greatly improve the respiratory compound in NEE.

Future ecological implications and feedbacks

The heath vegetation has previously been shown to benefit from increasing summer temperatures in the area (Groendahl et al., in press). In a climate change perspective where these ecosystems area expected to colonise the barren area (ACIA, 2005) this could result in higher biomass in the area and consequently high sequestration. In this study we have shown the plot-scale NEE from the fen dominated area to be high although temperature was high. These finding are supported by eddy covariance measurements from the fen areas in Zackenberg, where the strongest sink activity was seen in dry and warm growing seasons (Rennermalm et al., 2005). This is somewhat contrasting to the expected response in this vegetation type, which is discussed by Oechel et al. (1993; 1995) indicating that a warmer climate increase the active layer depth with subsequent lower water table and drier soils. However, measurements of the active layer depth in the area shows a clear increase during the summer months (ZERO, 2005). Additionally recent observations from the fen area indicate a decreasing water table depth (T.R. Christensen pers. comm.). Combined with the findings of (Christensen et al., 2000), who found that depth to the water table was positively correlated with respiratory rates in the fen areas, could lead to increased respiratory rates. The fen excerts a strong control on the area integrated flux from the region, although only covering 6.3% of the vegetated area it constitutes 81% of the mid summer flux (29 July). The future sequestration in the fen is consequently highly important for this particular High Arctic ecosystem. Consequently, applying this model to future scenarios should be done with caution as the future vegetation composition of the Arctic ecosystems in combination with changing environmental parameters e.g. air temperature, and thawing depth of the permafrost are determining for the Arctic landscapes role as a sink or source. Further, if this type of model should be used in future scenarios, data from more seasons should be included in the parameterisation of the model.

Conclusion

We have used two different models in assessing a regional CO_2 budget for a High Arctic region. The difference in flux estimates using the two methods was 2 fold for the upland areas in the region. The topography is important as the vegetation density decrease with elevation and consequently the AW is assumed to give too high result, whereas the SatModel takes into account the change in air temperature and vegetation density.

Consequently the results from this study indicates that the spatial and temporal variation in NEE can be predicted satisfactorily from a few measurable meteorological variables, photosynthetically active radiation, air temperature and satellite derivable data, a vegetation map and NDVI. Combined with the information on the spatial variations in landscape surface features, the models can be used as the basis for the temporal scaling of plot measurements of CO_2 exchange.

Applying models that requires a minimum data input is important in the Arctic, which by nature can be difficult assessing and it offers a good alternative to the more complex ecosystem models because the input data required for these models are lacking for most locations in the Arctic.

However as the shoulder seasons are not included in the estimate we are still far from an annual budget, but with the increasing summer temperatures in the region, we still believe that the region is in balance. How future climate scenarios will affect the balance is not clear, and more detailed models are needed for a future estimate on the annual balance.

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Table1. Area distribution of the vegetation classes in the region from A.P.Olsenland to Wollaston Forland. For the entire region a total of 12.3% is covered by vegetation. The classification of the Zackenberg valley based on aerial photography (Bay, 1998) is covering an area of 19 km^2, stretching from the lowlands up to 600 m altitude. Totally 68.5% of the classified area is covered by vegetation.

Landcover class	Dominating species	Zackenberg valley area (%)	Landsat TM classification of the region (%)
Fen	*Eriophorum scheuchzeri*, *Dupontial psilosantha*	14.8	6.3
Grassland	*Arctagrostris latifolia*, *Carex bigelowii*, *Eriophorum triste*, *Salix arctica*	26.6	38.8
Salix artica snowbed	*Salix arctica*	16.3	14.6
Heath (*Cassiope* and *Dryas*)	*Cassiope tetragona*, *Dryas* sp, *Salix arctica*, *Vaccinium uliginosum,* *Polygonum viviparum*,	42.3	40.3

Table 2. Accuracy assessment of the classification. Overall accuracy was 82.99% and the kappa coefficient was 0.808

	Reference data											
Classification	*Cassiope*	Abrasion	Snow	Grass	Fen	*Salix arctica* snowbed	Fell Field	River	Sea	Lake	Rock	Total
Unclassified	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cassiope	89.4	0.0	0.0	1.5	0.0	3.9	0.0	0.0	0.0	0.4	0.0	10.3
Abrasion	5.6	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	4.6
Snow	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.2
Grass land	3.8	0.0	0.0	65.8	33.0	39.2	0.0	0.0	0.0	0.0	0.7	13.1
Fen	0.0	0.0	0.0	0.0	65.9	17.6	0.0	0.0	0.0	1.2	0.0	5.0
Salix arctica snowbed	1.3	0.0	0.0	32.7	1.1	39.2	0.0	0.0	0.0	0.0	0.0	6.2
Fell Field	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	3.4
River	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	12.3	30.7	8.0
Sea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	5.8	0.0	10.4
Lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	80.4	0.0	14.4
Rock	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.4	6.4
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 3. Seasonal mean daytime CO_2 exchange as calculated by the two methods, SatModel and AW. Mean values (± SE) were calculated with the bootstrapping method. [a]Temporal integration of the satellite derived fluxes (DOY 177 to 231, n = 55). [b]Temporal integration of the fluxes from DOY 170 to DOY 243 (n = 74). The area integrated mean is the temporal integration of all vegetation types.

Vegetation type	SatModel derived[a] mg CO_2 $m^{-2}h^{-1}$	AW derived[a] mg CO_2 $m^{-2}h^{-1}$	Eddy Covariance mg CO_2 $m^{-2}h^{-1}$	SatModel derived[b] mg CO_2 $m^{-2}h^{-1}$
Heath	-77.6 ± 4.9	-126.7 ± 13.2	-185.1 ± 12.0	-56.6 ± 5.7
Grassland	-130.0 ± 10.7	-174.1 ± 12.6		-103 ± 9.9
Salix snowbed	-141.7 ± 16.1	-190.2 ± 20.8		-93.4 ± 16.3
Fen	-412.6 ± 22.7	-609.5 ± 32.9		-366.8 ± 22.3
Area integrated mean	-132.3 ± 10.0	-184.8 ± 14		-102.8 ± 10.0
Area integrated mean under 300 m.a.s.l.	-129.4 ± 10.9	-183.6 ± 14.2		
Area integrated mean over 300 m.a.s.l.	-81.0 ± 6.8	-164.9 ± 13.3		

Figures

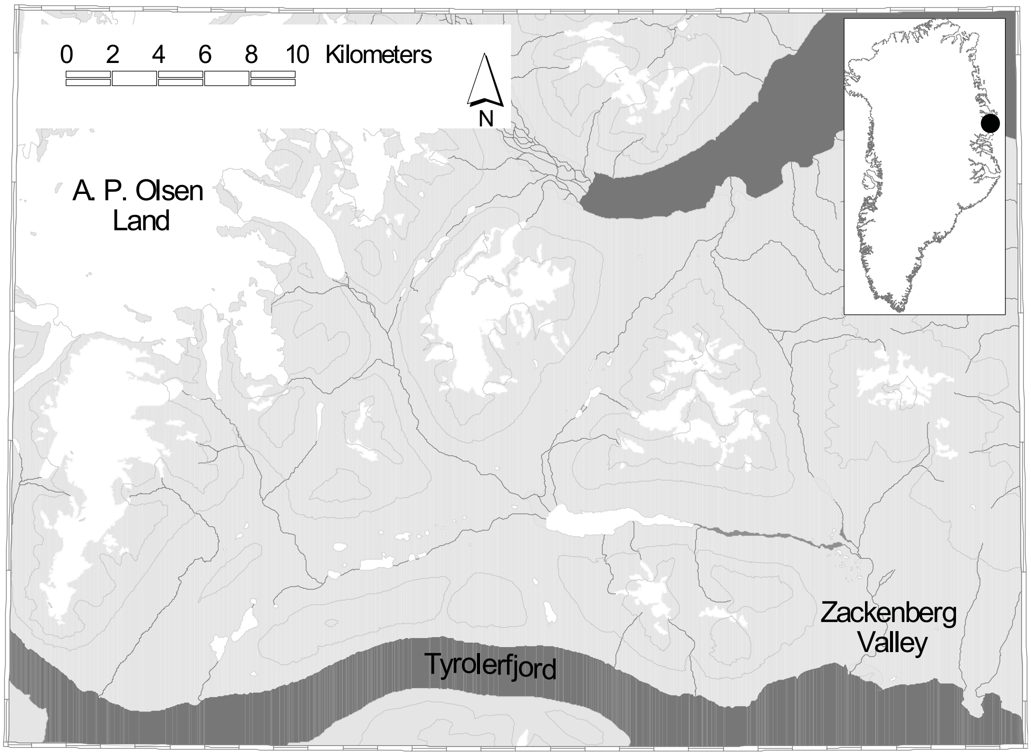


Fig.1. Area with A.P.Olsenland in the west and Wollaston Forland to the east. Zackenberg is located in the eastern part of the map. The equidistance at the contours is 500 meters starting at 0 ending at 1475m.

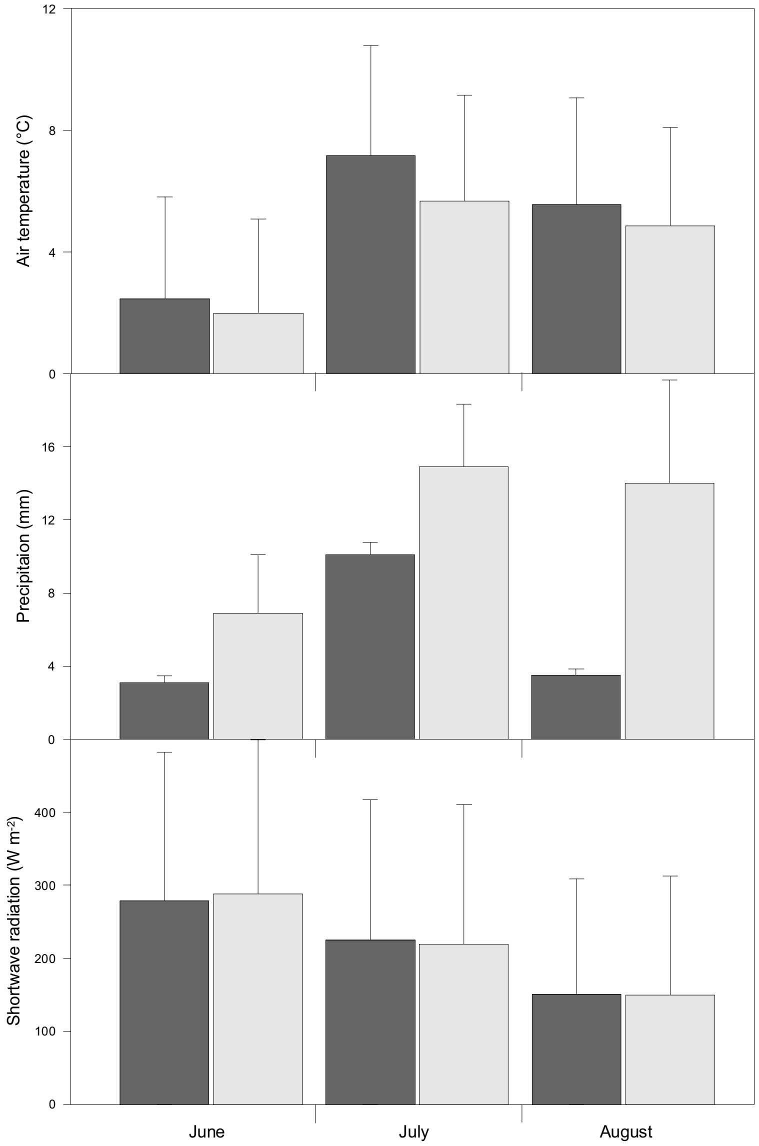


Fig.2. Climate variables, air temperature, precipitation and short wave radiation for 2004(dark) and the average period 1996-2004(light grey). Errorbars denotes standard deviations from the mean value.

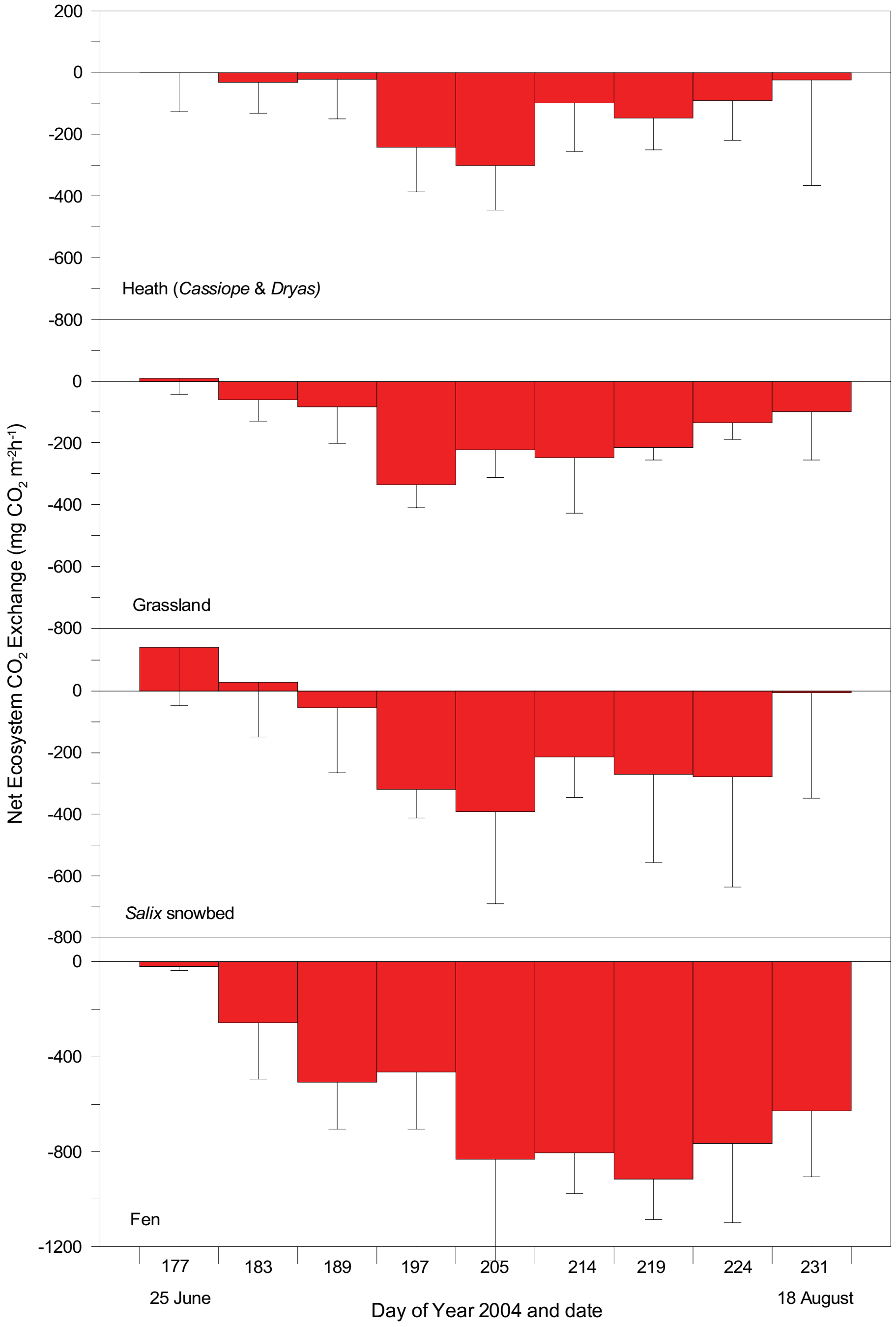


Fig.3. Average weekly daytime (10-16 hours) Net Ecosystem Exchange with standard deviations for the four vegetation communities found in the area. The Cassiope & Dryas is an area weighted flux estimate.

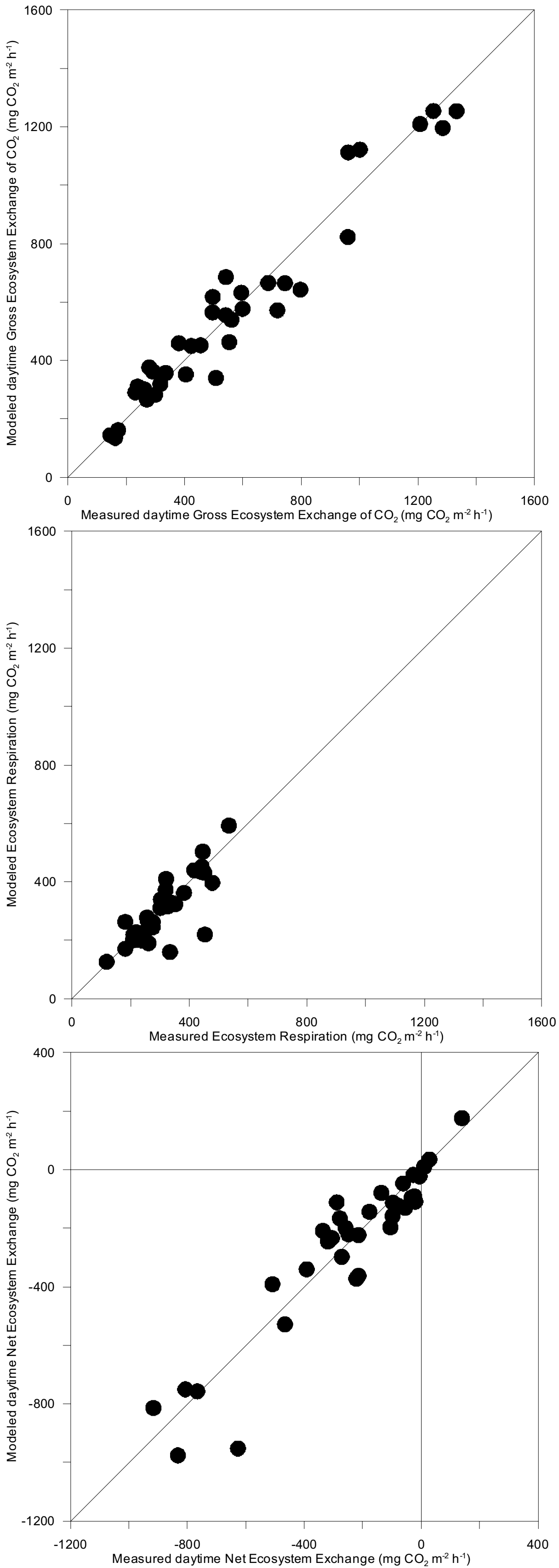
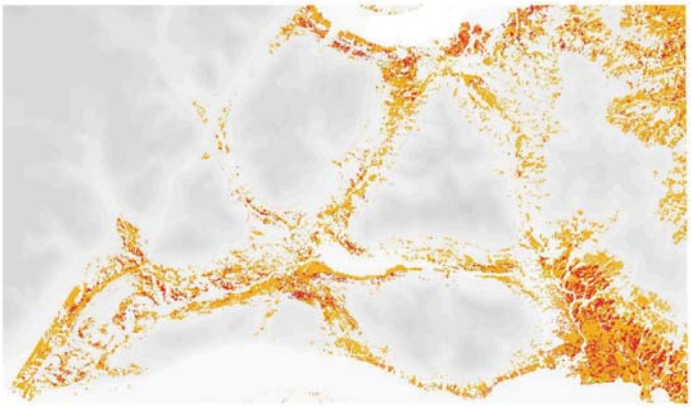


Fig.4. Modelled GEP (R^2=0.94), ER (R^2=0.7) and NEP (R^2 =0.88) plotted against measured fluxes for the nine week summer period. Negative values indicates uptake of CO_2.

Fig.5.



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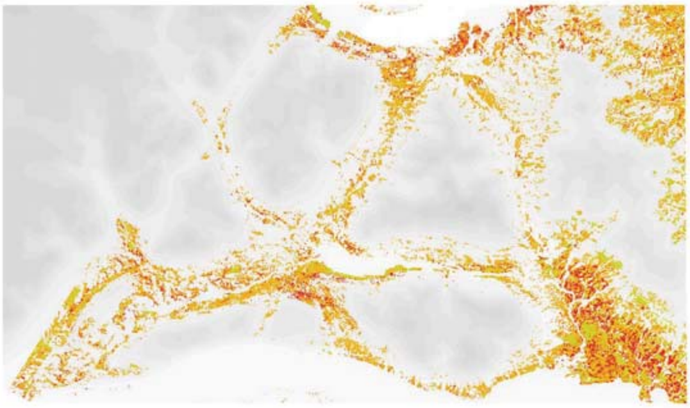

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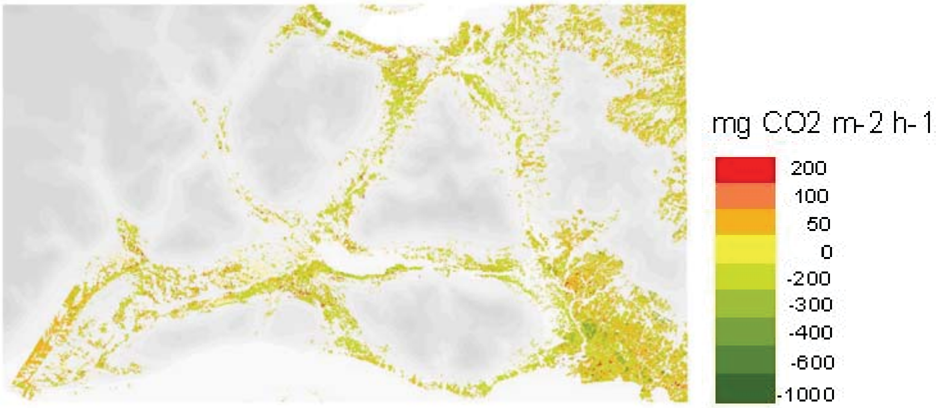

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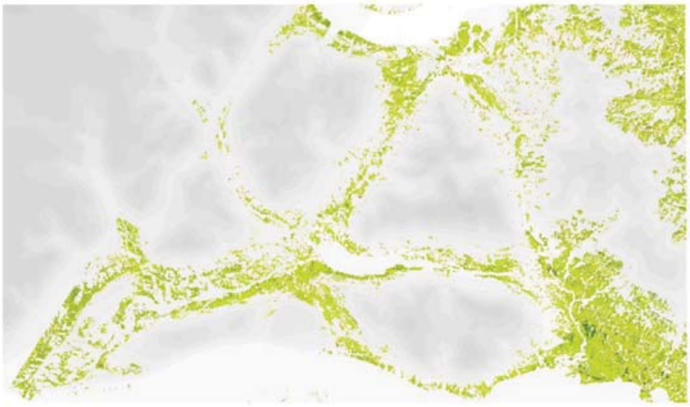
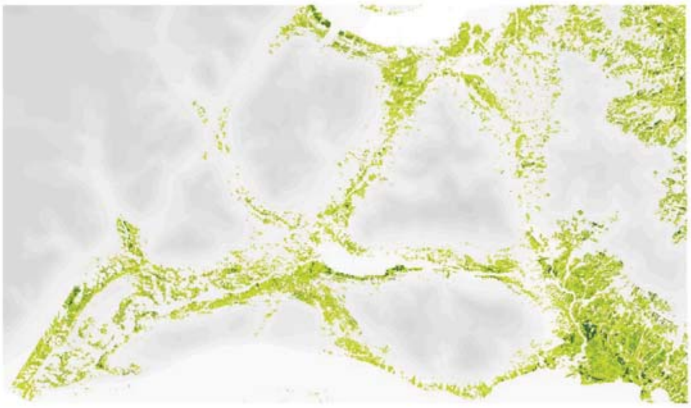
Fig.5. Continued



11 July 2004



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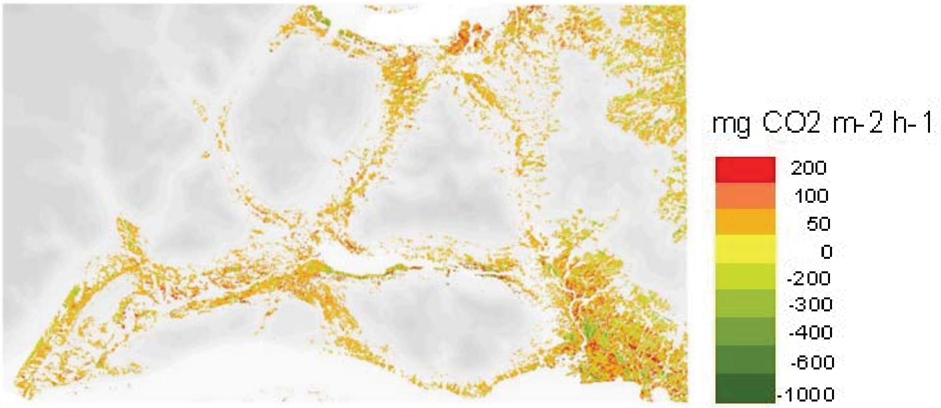

30 August 2004

Fig.5. Estimated daytime Net Ecosystem Exchange of CO_2 during the growing season from the beginning of the growing season, 18 June until the end by 30 August 2004. Estimates are obtained using the SatModel approach.

Fig.6.

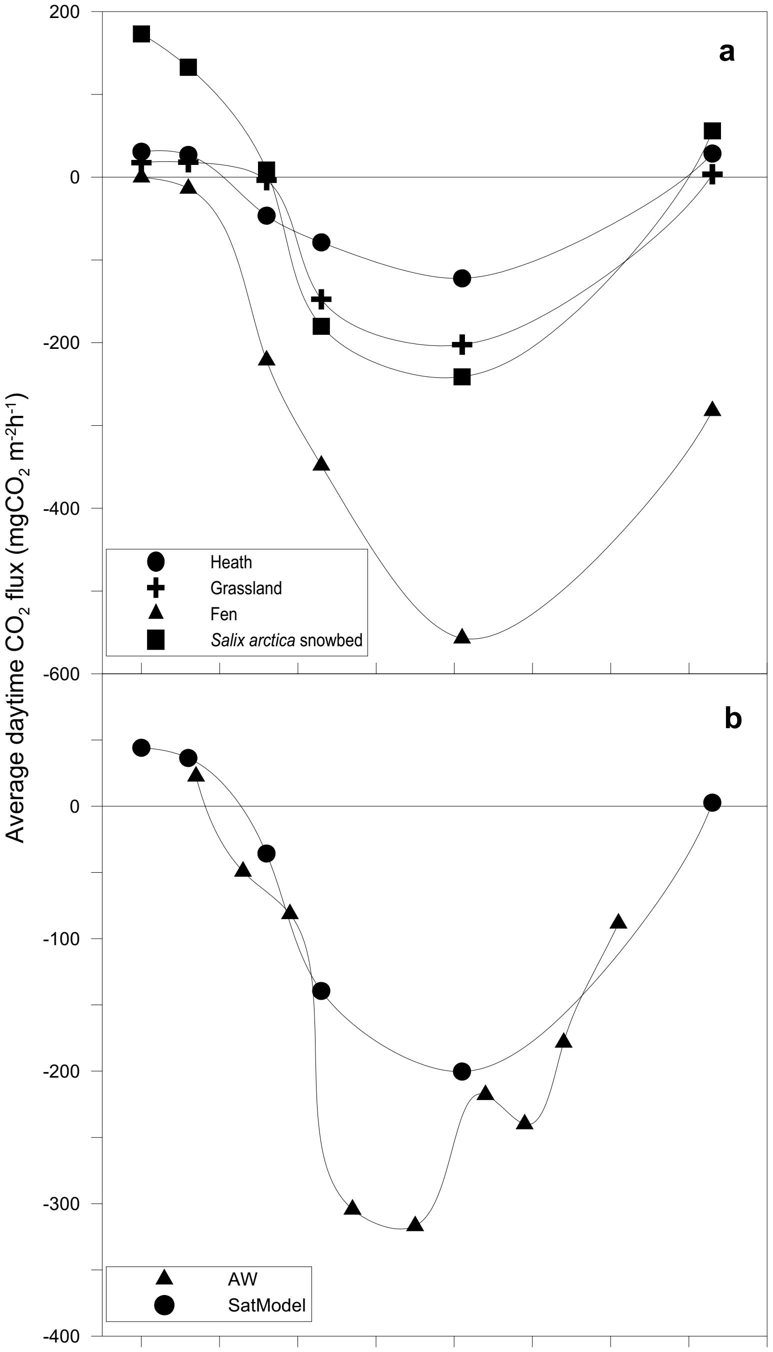

Fig.6. Average daytime regional scale fluxes for all four vegetation types, Heath (a composite of *Cassiope* and *Dryas*), *Salix* snowbed, Fen and Grassland (a), derived using the SatModel approach. The total integrated average daytime regional scale flux derived using the SatModel approach and the AW approach (b). Lines are spline fit of the data. Negative values denotes ecosystem uptake of CO_2.

Paper IV

Soegaard, H., Sørensen, L., Rysgaard, S., Grøndahl, L.,
Elberling, B., Friborg, T. S.E. Larsen and J. Bendtsen

High Arctic Carbon Sink Identification – A System
Approach

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High Artic Carbon Sink Identification – A Systems Approach

H.Soegaard, L.Sørensen, S.Rysgaard, L.Grøndahl,
B.Elberling, T.Friborg, S.E.Larsen and J.Bendtsen

The carbon budget of the High Arctic is one of the best indicators of the health of our planet. Over the last two decades climate models [e.g.1] have predicted that warming caused by elevated atmospheric CO_2 would be strongest and fastest in the Arctic. The most recent regional climate predictions are for an average Artic temperature increase of 1.7°C by the middle of this century, and location-specific temperature increases of 1 to 4°C [2]. Because of strong feedback mechanisms in the Arctic even moderate temperature changes may be amplified and result in large environmental responses.

In northern Scandinavia where annual average temperatures are around 0°C, recent warming has rapidly reduced the areas with permafrost [3] which could cause large increases in methane emission. Along the coast of northeast Greenland the lower average annual temperature (-10°C) means permafrost is less sensitive to warming. Here however, a clear response is seen in the decreasing extent of sea-ice. The effect on the terrestrial carbon balance is, however, not straightforward. On the one hand decreasing sea-ice leads to denser snow cover and shorter growing seasons with less carbon uptake, but on the other hand, actual CO_2 flux measurements show that carbon uptake in recent years has increased with the rising summer temperatures. Due to the multiple feedbacks, a systems approach, rather than a single process-study, is appropriate for determination of the High Arctic carbon budget.
In this article a summary of this approach is presented based on a number of Danish IGBP activities, and using the comprehensive data set from the Zackenberg research station (74.5°N, 20.5°W) and from the surrounding land and sea areas (Figure 1).

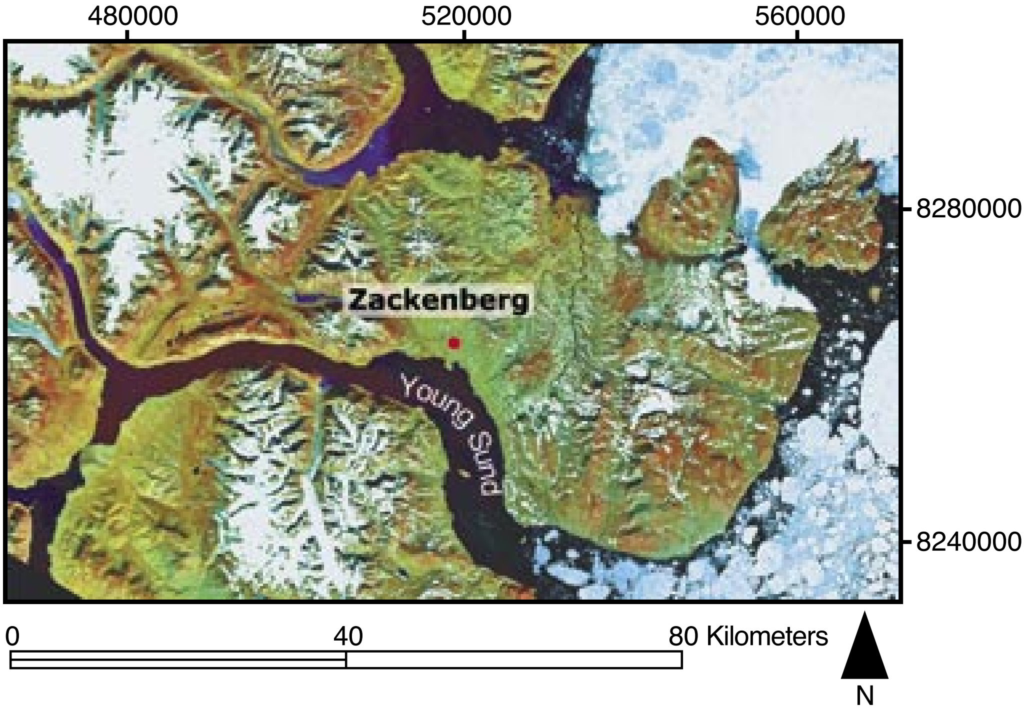

Figure 1. Landsat images of the Zackenberg study area. The red spot indicates the site of discharge and carbon measurements.

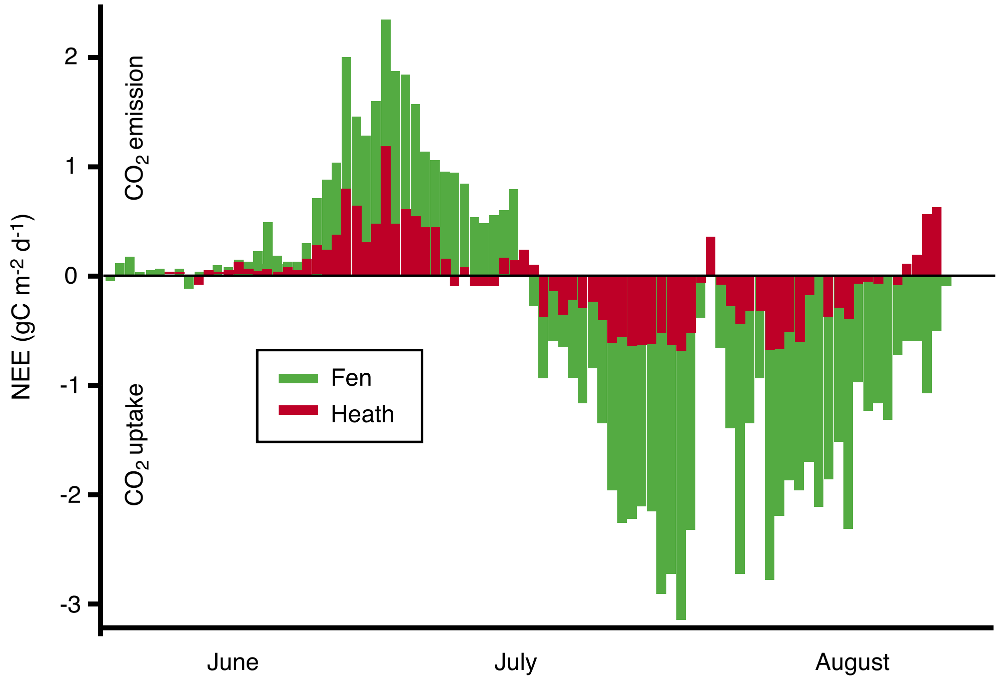

Figure 2. Temporal variation in Net Ecosystem Exchange (NEE) for two vegetation types (sedge-dominated fen and dwarf-shrub heath) for a selected year (1997).

Terrestrial Carbon Fluxes

During the summer the terrestrial ecosystem constitutes the upper step of the carbon cascade where CO_2 fixation takes place nearly 24 hours a day due to the midnight sun. Summer CO_2 fluxes have been recorded for two contrasting vegetation types: a sedge-dominated fen (1996-1999) [4] and dwarf shrub heath (1997, 2000-2004). The temporal variation in CO_2 exchange (Figure 2) shows CO_2 emission in late June when the snow disappears from both vegetation types. CO_2 emission from the fen however, is greater due to the higher soil carbon content. In July, when the leaves develop, the ecosystem is rapidly transformed into a net carbon sink due to the relatively high photosynthetic rates during the peak growing season. From early August, lower sun angles and leaf senescence cause carbon sequestration to diminish, and whilst the fen continues as a net carbon sink until the end of August, the heath becomes a net carbon source from as early as mid-August. Combining these areal carbon sequestration rates with the areal extent of the two vegetation types in the study area (Figure 1) provides an estimate of the terrestrial carbon balance for the summer (10 g m^{-2} per season) [4]. Applying a soil respiration model allows estimation of the winter carbon budget, and summing the winter and summer budgets provides an estimate of the annual budget (Table 1). This budget includes the carbon emitted as methane (15 g m^{-2} yr^{-1}) from the fens covering 2-3% of the area.

Carbon Transport Through the Fluvial System

Carbon is transported through the High Arctic rivers during an intensive 3-4 month period (June-September). The peak discharge occurs in June-July associated with snowmelt. Carbon is transported to coastal waters in both dissolved forms and particulate forms (particulate organic carbon – POC). The dissolved carbon comes partly from the decomposition of soil organic matter and partly from the dissolution of soil carbonate minerals. Over the summer the average carbon concentration is usually relatively constant at around 4-5 mg L^{-1}, although the concentration can as much as double in connection with landslides. POC transport is equivalent to about one quarter of the dissolved carbon transport, but

Component	Type	Ice	Area	Atmospheric Flux (A)		Fluvial Transport (F)		Lateral Marine Transport		Net Flux	Net change in storage
		%	km^2	t yr^{-1}	g m^{-2} yr^{-1}	t yr^{-1}	g m^{-2} yr^{-1}	t yr^{-1}	g m^{-2} yr^{-1}	g m^{-2} yr^{-1}	g m^{-2} yr^{-1}
Zack Basin	Terrestrial-Fluvial		512	**-1,200**	**-2.3**	**-1,400**	**-2.7**	0.0	0.0	**-0.4**	not available
Young Basin	Terrestrial-Fluvial		3,100	-4,700	*-1.5*	4,600	-1.5	0.0	0.0	0.0	not available
Young Sund	Coastal	80	396	-1,560	**-3.9**	-4,600	-12	**-2,800**	**-7.1**	**-23**	**-19**
Greenland Sea	Marine	20	300,000	-13x10^6	**-42**	0.0	0.0			-42	**-2.0**

Table 1: Carbon exchanges by study area component. Values given in bold are based on in-situ measurements and values given in italics are found by satellite based up-scaling. Downward directed fluxes are negative, upward fluxes are positive.

it nearly doubles at the time of the maximal biological activity in early August. Based on four years (2000-2003) of summer measurements at Zackenberg the total (dissolved and suspended) fluvial carbon transport is estimated to be approximately 1,400 t. Distributing this amount equally over the upstream drainage basin (512 km^2) gives an estimated areal annual carbon flux of approximately 2.7 g m^{-2} which is nearly equal to the terrestrial carbon fixation (Table 1).

CO_2 Fluxes over the Arctic Ocean

The open Arctic seas function as a year-round carbon sink pumping atmospheric CO_2 into the sea and thereby producing dissolved inorganic carbon (DIC). The uptake rate is largely controlled by the CO_2 difference across the air-sea interface (ΔCO_2), the presence of sea-ice and the atmospheric wind forcing of the surface waters. During winter an under saturation of CO_2 is maintained in the open sea because of the higher solubility of CO_2 at low temperatures and because the stronger winds enhance the transport of CO_2 across the sea surface. During summer the CO_2 difference is larger because micro-organisms transform DIC into organic compounds that sink deeper into the sea, however, the winds are calmer. Based on modelling [5] the carbon (as CO_2) flux from the atmosphere to the Arctic sea is assumed to be relatively constant with average monthly fluxes ranging from 2 to 6 g m^{-2}. These estimates are verified by recent observations collected during three research cruises in the North Atlantic and the Greenland Sea (Figure 3), which despite scatter due to differences in season and weather indicate that the largest ΔCO_2 is located in the Artic rather than in the North Atlantic. Assum-

> "The open Arctic seas function as a year-round carbon sink pumping atmospheric CO_2 into the sea..."

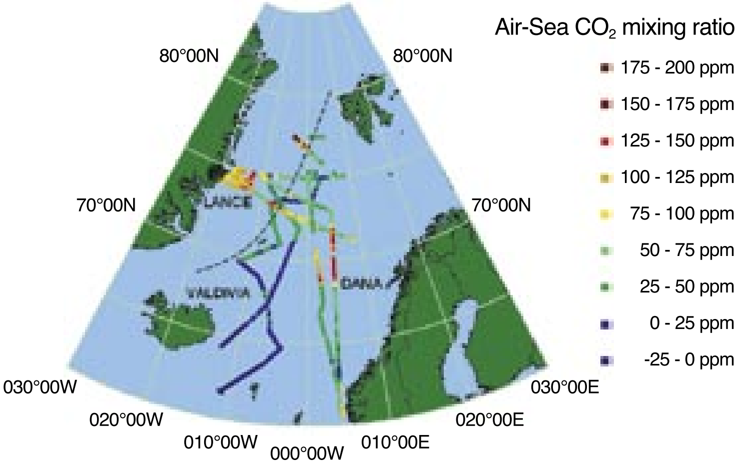

Figure 3. Air-sea mixing ratio measured during three different cruises in the northern north Atlantic: Valdivia (April 1999), Dana (June 1999), Lance (October 2003). The dashed line encircles the High Arctic observations.

ing that the three sampling months (April, June, October; Figure 3) are representative of the annual range of conditions, the annual carbon uptake by the ice-free part of the Greenland Sea is 52 g m^{-2}, which is in accordance with Anderson et al. [5]. Because the sea ice puts an effective lid on the air-sea exchange, the actual uptake is assumed to be proportional with ice-free fraction of the sea which varies with the distance from the coast. In winter dense drifting ice is normally found up to a distance of >200 km from the coast whereas in late summer the sea ice becomes a narrower band (<100 km) with discontinuous ice. Long-term ice cover records shows a spatial variation from 80% in the inner fjords to 20% in the Greenland Sea [5] (Table 1).

Carbon Deposition in the Fjord System

The extensive 396 km^2 Young Sund fjord system functions as the lowest step on the carbon cascade collecting fluvial carbon from a 3,100 km^2 drainage basin, marine carbon from the Greenland Sea and CO_2 from the atmosphere. By scaling the fluvial carbon measured at the Zackenberg site (1,400 t yr^{-1}) up to the whole Young Sund drainage basin suggests an export of 4,600 t yr^{-1}, which distributed over the entire drainage area gives an annual areal carbon export of 11.8 g m^{-2}. Hydrographic observations [6] give an estimate 35.1 t d^{-1} for the marine net carbon inflow from the Greenland Sea, which scaled to the area of the fjord corresponds to a net carbon input of 0.09 g m^{-2} d^{-1}, or 7.1 g m^{-2} for the summer. The atmosphere is the third carbon source. CO_2 gradient measurements across the sea-air interface suggest average atmospheric carbon fluxes (as CO_2) of 0.05 g m^{-2} d^{-1}. Based on an 80 day productive summer period this corresponds to an annual carbon flux of 3.9 g m^{-2}. Comparing the sum of the annual oceanic, the fluvial and atmospheric carbon contributions (23 g m^{-2}) to annual vertical carbon fluxes of 19 g m^{-2} measured at a depth of 66 m [7] the systems approach is again demonstrated to be effective in reducing the uncertainties in carbon budgets.

For the terrestrial-fluvial system there is reasonable balance between sources and sinks (deviation less than 20%), and for the coastal ecosystem the net carbon flux is very similar to sediment trap measurements that indicate accumulation in storage (two right-hand columns of Table 1). For the Greenland Sea however, there is a huge discrepancy between the net surface flux and measured sedimentation (net change in storage). This is largely because the carbon uptake by the surface waters (0-150 m) is mixed down to the deep layers and will remain isolated from the atmosphere for centuries. To balance this budget we must assume a lateral transport of 40 g m^{-2} yr^{-1}. An improved carbon budget would thus require detailed ocean modelling as well as data for historic climatic trends and wintertime processes.

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Paper V

Christensen, T.R., C. E. Tweedie, T. Friborg, M. Johansson, P. M. Crill, J. A. Gamon, L. Groendahl, J. Gudmundsson, Y. Harazono, C. Lloyd, P. J. Martikainen, W.C. Oechel, H. Oskarsson, N. Panikov and P.A. Wookey

Carbon fluxes and their controlling processes in Arctic tundra: Current knowledge and challenges

Submitted *Ecological Applications*

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Carbon fluxes and their controlling processes in Arctic tundra: Current knowledge and challenges

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Abstract

Carbon cycling in the circumpolar tundra regions has attracted a lot of attention in recent years. Major reasons for this include the substantial carbon stored as soil organic carbon and the associated potential feedback effects in a changed climate through potential release of this carbon as greenhouse gases carbon dioxide and methane. Despite much research recent major international assessments such as the Arctic Climate Impact Assessment and the Millenium Ecosystem Assessment have not been able to come up with a conclusive answer as to whether the Arctic is currently a source or a sink for atmospheric carbon dioxide. The current paper aims at providing a review of the available information based on observational evidence and process studies to help answer this question with attention also made to the important methane emissions from arctic tundra regions. The paper has a section on process understanding followed by a review of the available seasonal/annual carbon dioxide and methane flux studies from the circumpolar North. We conclude that based on the currently available information the circumpolar North is roughly in balance with respect to carbon dioxide exchanges with some regions showing signs of current losses and others sink functioning. Taking into account the methane emissions, however, and seen over a decadal timescale, the circumpolar North is considered to be a current source of radiative forcing. Whether this source functioning will continue into the future is uncertain and will depend on the fate of permafrost, soil moisture and surface hydrology and the future state of ecosystem structure and function in the high arctic.

Key words: Arctic tundra, carbon balance, carbon dioxide (CO_2), methane (CH_4), ecosystem function, trace gas flux, biogeochemical cycling, global change

Introduction

Arctic terrestrial ecosystems have attracted extraordinary attention in the context of global carbon cycling in recent years (ACIA 2005, Millenium Ecosystem Assessment 2005). A reason for this is that Arctic terrestrial ecosystems store a significant proportion of the global stock of soil organic carbon (C). In the arctic tundra proper, some 121-191 Gt of C are stored, or approximately 12-16% of the estimated world total (McKane et al. 1997, Tarnocai et al. 2003). If boreal ecosystems are included, this estimate rises to almost 30%. Arctic regions (Figure 1) are predicted to undergo significant changes due to anthropogenic climate impacts (Kittel et al. 2000, IPCC 2001, Wookey 2002, ACIA 2005, Lawrence and Slater 2005). These changes and the feedbacks they engender could change the climatic conditions that have allowed the development of such large soil C stocks in the Arctic (Gorham 1991, Shaver et al. 1992, McKane et al. 1997, Hobbie et al. 2000). Extensive regions of the High Arctic that lack substantial C stocks and currently have very limited rates of atmospheric exchange could develop dynamic C cycles. Climate driven changes in plant community structure, specifically shifts from herbaceous and cryptogamous dominance to systems dominated by ericaceous and woody species, are also likely to change ecosystem C dynamics and balance.

Arctic soils are often wet and, when waterlogged, become anoxic (Figure 2). Anaerobic soils often accumulate C in the form of peat (Gorham 1991, Clymo et al. 1998) and release methane (CH_4), a radiatively important trace gas (Matthews and Fung 1987, Joabsson and Christensen 2001, Öquist and Svensson 2002). Methane flux is rarely a quantitatively important component in the ecosystem C balance but it can play a disproportionately important role in terms of greenhouse gas forcing (gram for gram methane in the atmosphere has 23 times the radiative forcing potential of CO_2).

The potential socio-economic and cultural implications of climate change demand quantitative understanding of the interactions, processes and the balance of forcing factors and their feedbacks of natural and anthropogenic systems. The C balance of the Arctic terrestrial realm is one such system. This paper aims at providing an overview of our current understanding of the circumpolar terrestrial ecosystem carbon balance from an observational and process understanding point of view. It is meant to compliment a companion paper (Sitch et al., this issue) which is focusing on the current status of modelling and remote sensing of the circumpolar carbon balance. The manuscript is organised in two major sections, one on processes and controlling factors and a second on a review of actual flux observations in the circumpolar North.

Background and processes

Processes controlling carbon budgets in arctic ecosystems vary across a continuum of space (plot to region) and time (minutes to decades), and varying classes of biological complexity (e.g. from individual species, through trophic interactions, to whole ecosystems). Thus, determining an accurate C budget for the Arctic requires a foundationally extensive and sustained observational capacity, which incorporates measurements and instrumentation that are sensitive to processes influencing C uptake, storage and loss. The latter is arguably the greatest source of current scientific uncertainty due to significant uncertainties remaining in the mechanistic understanding of processes controlling C losses, whereas accurate scaling across space and time is perhaps more constrained by logistical and funding limitations. Here, we discuss the importance of several important processes controlling C uptake, loss and storage in arctic tundra. Factors that are important for scaling process studies across space and time are considered below.

There are a finite number of basic processes involved in controlling CO_2 exchange. Net ecosystem production (NEP) of organic carbon is the net product of two independent processes that drive the uptake and release of C; gross primary production (GPP) and respiration (both autotrophic and heterotrophic, CO_2 as well as CH_4; Figure 2). The net annual C budget of a given ecosystem is also affected by export of dissolved and particulate organic C in ground and streamwater flows (Michaelson et al. 1998; Tipping et al. 1999; Cole et al. 2002; Judd and Kling 2002), which are relatively unknown for the Arctic. Despite the capacity for C transport in Arctic soils and streams (Kling et al. 1991; Judd and Kling 2002) these are probably minor relative to the release of volatile organic compounds (Kesselmaier et al., 2002). The net annual C balance or budget is the result of both independent and coupled (e.g. Boone et al. 1998; Högberg et al. 2001) processes that often respond differentially to the same abiotic forcing factors; this makes interpretation and prediction of their quantitative impact a major challenge.

The net emission of CH_4 from a given ecosystem is also the result of a complex set of independent processes that regulate production, oxidation and transport (Figure 2). Controls on these processes include soil temperature, plant species composition (and functional type), and factors that influence the redox potential (Eh) of the soil environment (e.g. the position of the water table) (Moore and Knowles 1989, Christensen 1993a, Funk et al. 1994, Yavitt et al. 1997, Bellisario et al. 1999, Christensen et al. 1999, Christensen et al. 2000, Joabsson and Christensen 2001, Öquist and Svensson 2002, Sjögersten and Wookey 2002, Blodau and Moore 2003, Ström et al. 2005). Also, as is the case for CO_2 exchange, the temporal dynamics of net CH_4 fluxes between a given landscape and the atmosphere can be highly variable due to contrasting processes controlling exchange at different times of the year. Permafrost dynamics impact all these factors (Figure 1) in arctic, subarctic and some boreal ecosystems. Thus, changes in the permafrost regime (Christensen et al., 2004, Lawrence and Slater 2005) will have fundamental consequences for CH_4 and CO_2 fluxes in the Arctic.

Table 1 provides an overview of exogenic and endogenic factors controlling carbon fluxes in Arctic terrestrial environments. The following provides a detailed discussion of these factors.

Carbon Uptake

The processes controlling the net uptake of atmospheric CO_2 in Arctic terrestrial ecosystems (NPP in Figure 2) are relatively well understood compared to processes controlling C loss and storage (Table 1). Sampling techniques cover a spectrum of temporal and spatial scales with well-developed methods, including soil C accumulation (Marion and Oechel 1993, McKane et al. 1997, Trumbore 2000), biomass harvests (Shaver et al., 1998), chamber gas exchange (Sebacher et al., 1986, Whiting et al., 1992, Oechel et al., 1993, Christensen et al., 2000), eddy correlation methods (Fan et al., 1992, Nordstroem et al., 2001), and remote sensing approaches (Myneni et al., 1997, Soegaard et al., 2000, Sitch et al., this issue). New techniques are continually being developed e.g. isotopic analyses (Levin and Hesshaimer 2000, King et al. 2002, Olsrud and Christensen 2004) and the utilization of organic tracers such as amino acids (Huang et al. 1996, 1999).

Fundamentally, C uptake rates in arctic ecosystems are limited by low temperature, short growing seasons, and often low quantum yield. Additionally, limited water and nutrient availability can further reduce uptake during the snow-free period (growing season) in many microhabitats and regions of the Arctic (Figure 3 and 4) whilst increased CO_2 concentration in combination with increased temperature appears to increase uptake at least in the short term (Oechel et al. 1994). Increasingly, it has been observed that various drivers work in synergistic ways. For example, under high light and low temperature conditions, photoinhibition can occur, a phenomenon that can be further exacerbated by nutrient deficiencies, water deficits and/or temperature extremes. Thus, changes in any of these factors could potentially alter the incidence of photoinhibition. Studies have also identified the sometimes contrasting patterns in the efficiency of C uptake, sensitivity to stress and seasonal phenology of differing plant functional types and land cover classes (Christensen et al. 2000, Jones et al. 2000, Vourlitis et al. 2000). For example, cryptogams (mosses and lichens) are particularly susceptible to moisture stress (Harley et al. 1989) and photoinhibition (Murray et al., 1993), whereas most vascular plants are buffered against these stresses due to the presence of roots and different storage and conductive mechanisms. The response of ecosystems to altered climatic conditions depends upon the nature of the perturbation, site history and the vegetation community/ land cover type (Forbes et al. 2001). Crucial to the response of vegetation communities will be the competition, acclimation and adaptation potential of species over various but lagged response times (Marchand et al. 2005, Arft et al. 1999, Walker et al. 2006).

Despite our considerable knowledge of the factors regulating C uptake in arctic ecosystems, there remain significant challenges in sampling both CO_2 and CH_4 and integrating sampling methods across multiple spatial and temporal scales (Vourlitis et al. 1993). Eddy flux correlation towers exist (or have temporarily been deployed), in a few arctic sites as reviewed below, but vast reaches of the Canadian, Russian and

Siberian Arctic remain essentially unstudied (Running et al. 1999, Zamolodchikov et al. 2003, http://www-eosdis.ornl.gov/FLUXNET/). In spite of the excellent temporal resolution and fairly large spatial scale flux integration, eddy correlation methods cannot easily isolate dark respiration from net fluxes due to the lack of summer darkness. Neither can the method easily partition the flux into its sub-footprint spatial components for long periods of stable (most often nocturnal) rather than mixed boundary layer conditions. The footprint of eddy towers is also highly transient compared to static chamber techniques, and mostly dependent upon wind speed and boundary layer conditions. Accurate measurements are difficult to make at both high and low wind speeds using eddy covariance methods (Vourlitis et al. 2000). Nevertheless, quantifying gross uptake of CO_2 at the landscape scale is important for validating remote sensing products that utilize light-use efficiency algorithms and measures of vegetation productivity, such as the Normalized Difference Vegetation Index (NDVI), to model ecosystem productivity (Stow et al. 2003, Running et al. 2004) and to constrain extrapolations of small chamber scale flux measurements. Chamber flux methods (including automated systems) contribute to the quantitative resolution of flux components, but these methods are limited temporally and spatially by the small sampling area and the need for significant human resources to maintain equipment and high frequency sampling under all types of weather. Additionally, we now have daily satellite coverage of the Arctic (e.g. EOS Aqua and Terra platforms, together with several other polar orbiting satellites). Most of these utilize optical sensors that are problematic in the Arctic due to low sun angles, persistent or frequent cloud cover, and the abundance of standing water, snow, and ice, all of which pose problems for current satellite vegetation indices (Stow et al. 2004). These remote sensing technologies also differ in their spectral and spatial resolution, presenting challenges for interpretation and inter-comparison (Steven et al 2003, Raupach et al. 2005; Gamon et al. in review). Radar remote sensing technologies offer new methods for detecting key seasonal events (e.g. snow melt and spring break-up) (Frolking et al., 1999), soil moisture (Kane et al. 1996), and plant biomass (Rauste 2005), but adequate means for translating this information into carbon uptake show great promise in Boreal forest (Le Toan et al. 2004) but still require refinement for use in arctic tundra systems. Table 2 gives an overview of methods available and what they can produce in terms of information on carbon uptake and losses.

Carbon Loss

The massive stores of carbon in high northern latitudes are the result of slow decomposition, not excessive uptake (Flanagan and Veum 1974, Swift et al. 1979, Raich and Potter 1995, Frolking et al., 1997, Clymo et al. 1998, Hobbie et al, 2000, Raich and Tufekciouglu 2000). The very factors that have resulted in the accumulation of C in soils and sediments in this region may also, however, predispose them to instability in the context of global change, with major implications for gaseous C losses. It has been hypothesized, for example, that soil organic matter (and thus C) at high latitudes shows a lesser degree of 'chemical stabilisation' (decomposition is constrained to a greater extent by environmental conditions than by resource quality) than soils in warmer ecosystems (Giardina and Ryan, 2000, Fang et al., 2005), and decomposition could therefore be dramatically enhanced under ameliorated environmental conditions. Superimposed upon this factor are the hypothesised enhanced microbial responses to small changes in temperature and moisture in these more environmentally extreme systems (Elberling and Brandt, 2003).

In general, our understanding and parameterization of the processes underlying C release is also much less developed than our understanding of photosynthesis. This is partly because C loss is the product of a complex and strongly coupled suite of processes that appear to respond to environmental change drivers differentially (Silvola et al. 1996a, Liski et al. 1999, Fang and Moncrieff 2001, Högberg et al. 2001, Joabsson and Christensen 2001). As such, accurate representation of C loss remains a major challenge for quantitative modelling of C fluxes. This results in serious gaps in our understanding of environmental change impacts upon these processes due to:

- methodological problems (e.g. partitioning autotrophic and heterotrophic respiration (Figure 2); adopting comparable measurements across environmental gradients) (Silvola et al. 1996b, Boone et al. 1998);
- the lack of a well-developed conceptual framework for coupling above and below-ground processes in ecosystems, while maintaining the functional integrity of plant-soil couplings (e.g. linkages between GPP and root respiration, exudation and rhizosphere processes; intra-plant carbon allocation, plant mediated transport of CH_4 and O_2) (Chapin and Ruess 2001, Högberg et al. 2001, Joabsson and Christensen 2001, Christensen et al. 2003a);
- problems characterizing functional and taxonomic biodiversity of soil organisms (e.g. Copley 2000) and;
- poorly-developed methodologies for characterizing soil organic matter (SOM) lability/biochemistry (Liski et al. 1999, Sjögersten et al. 2003) and transport.

Biological processes resulting in gaseous C losses include heterotrophic respiration, autotrophic respiration, fermentation, methanogenesis and methane oxidation (Figure 2). Physico-chemical drivers include many permafrost and surface hydrology-related parameters such as soil temperature, soil moisture and water table depth, in addition to parameters such as soil texture, mineralogy and surface age (Walker et al. 1998). Importantly, exchange of C between arctic terrestrial ecosystems and the atmosphere is highly sensitive to drivers that are operating at many different temporal and spatial scales in response to global and/or natural successional change, including permafrost conditions and active layer dynamics (Flanagan and Veum 1974, Christensen et al. 1998, Christensen et al. 1999, Sjögersten and Wookey 2002, Grant et al. 2003).

In spite of this, even the basic temperature response kinetics of processes releasing C to the atmosphere are extremely complex to investigate, quite apart from any systematic consideration of the effects of varying soil moisture content (Davidson et al. 1998). Some of the key unresolved issues concerning aerobic soil respiration alone (and ignoring anaerobic respiration, methanogenesis and methanotrophy) include:

- Lack of understanding of the contribution of different SOM fractions (and ages) (e.g. recent leaf and root litter, rhizodeposits, humified organic matter) to CO_2 emissions through soil respiration (Gaudinski et al., 2000, Trumbore, 2000, Fang et al., 2005, Schimel and Mikan, 2005);
- Lack of understanding of the role of SOM quality (i.e. its substrate quality or relative recalcitrance) in modulating temperature responses and the variability of this response through time as the more labile SOM fractions become exhausted (Liski et al., 1999, Ågren, 2000, Giardina and Ryan, 2000);
- Inability to assess the temporal stability (or otherwise) of temperature response kinetics (Reichstein et al., 2000, Dalias et al., 2001, Sjögersten and Wookey, 2002);

- Poorly quantified contributions of root respiration to total CO_2 emission and temperature responses (Boone et al., 1998, Högberg et al., 2001, 2002), and understanding the role of the rhizosphere in SOM dynamics (Kuzyakov et al., 2000), Factors that directly affect primary productivity can also indirectly control C losses by influencing the quantity and quality of organic matter inputs to soils and sediments where heterotrophic respiration and/or methanogenesis occurs (Silvola *et al.* 1996, Högberg *et al.* 2001), as well as influencing rates of root respiration directly; and
- Insufficient information on, and understanding of, the spatial distribution of SOM pools in landscape and regional settings (Bednorz et al., 2000, Walker 2000).

We are also faced with the complexities of integrating and scaling measurements over both time and space. Winter processes, for example, are poorly studied due both to logistical difficulties and to traditional (but erroneous: see Clein and Schimel 1995, Oechel et al. 1997 Fahnestock et al. 1999, Elberling 2003) notions that biological processes below 0°C are sufficiently slow that they are unimportant biogeochemically. There is growing evidence, however, of continuing respiratory activity at temperatures as low as -30 ºC (Panikov et al., 2005). Importantly, at higher temperatures (between 0 and -15 ºC, for example), continuing production of CO_2 and CH_4 under snowpack and in frozen soils is sufficient during a long winter season to contribute significantly to annual losses of C (Figure 3, Oechel *et al.* 1997, Grogan et al. 2001, Nordstroem *et al.* 2001, Aurela et al. 2002). Winter processes are also potentially of great importance to the subsequent summer processes, affecting for example the onset of thaw, length of the active season and hydrolytic activity (Aurela et al., 2004). The lack of sustained integrated, long term and multi-variable time series data limit our understanding. The discovery of biological processes occurring at very low temperatures (mentioned above) and the recent report of aerobic, perhaps abiogenic, methanogenesis associated with plants (Keppler et al. 2006), force us to reassess continually our understanding.

Figure 3 shows how processes controlling C losses are highly sensitive to soil hydrology, which has a profound effect on the soil redox potential (Moore and Knowles 1989, Moore and Dalva 1993, Funk et al. 1994, Silvola et al. 1996a, Aerts and Ludwig 1997, Yavitt et al. 1997, Oechel et al. 1998, Öquist and Sundh 1998, Blodau and Moore 2003, Huemmrich et al., in prep.). In the Arctic, soil hydrological regimes are strongly influenced by topography and permafrost distribution/depth, time of year in relation to spring snow and soil thaw, evapotranspiration and site history (Walker et al. 1998, Rouse 2000, Walker 2000). Respiratory processes and methanogenesis respond differently to moisture. Waterlogging favors methanogenesis by slowing O_2 diffusion and lowering Eh. Soil drainage allows more effective O_2 diffusion, potentially (depending on other factors, such as temperature and oxygen demand) enabling aerobic oxidative metabolism to contribute to more efficient organic matter remineralization and more rapid respiration (Billings et al. 1982, Moore and Dalva 1993, Oechel et al. 1993, 1998, 2000a, Öquist and Sundh 1998).

Figure 4 further emphasises the importance of the soil moisture regime in controlling net changes in CO_2 and CH_4 emissions from tundra ecosystems. T also emphasises the microtopographical complexity we are faced with where with only a few meters distance clearly different responses to the same environmental change (in this case soil moisture) may be found. Such small scale complexity represents a major challenge for scaling up and modelling tundra ecosystem responses to climate change.

Carbon Storage

Carbon storage is the sum of net carbon uptake, '*sinks*', and net carbon loss, '*sources*'. The existence of peat and organic rich soils indicate that most tundra in the Arctic has been a net sink for C throughout the Holocene due to lower rates of decomposition relative to rates of C uptake (Marion and Oechel 1993). Understanding how changes in ecosystem level production and decomposition interact and potentially offset the balance and stability of the Arctic soil C reservoir is a priority for global climate change science. If there is a net loss of soil C to the atmosphere in the form of greenhouse gases (namely CO_2 and CH_4), warming could be enhanced. This potential positive feedback response could cause Arctic terrestrial ecosystems to enter a state that appears to be have been unprecedented during the late Holocene. Given the enormous stores of carbon in the Arctic described above, the relative residence times of various greenhouse gases in the atmosphere (IPCC 2001), the importance of the 0°C freezing point threshold to arctic ecosystem structure and function (Outcalt et al. 1990, Clein and Schimel 1995, Elberling 2003, Christensen et al., 2004, Schimel and Mikan 2005) and the very nature of this potential feedback response, net exchanges of carbon to the atmosphere from arctic soil organic pools are likely to have globally significant implications (Chapin et al. 2000, Millenium Ecosystem Assessment 2005). As mentioned earlier, however, these positive feedback mechanisms in a climate context must also be balanced against the potential extra uptake and accumulated soil carbon in currently high arctic areas with little soil C storage (ACIA, 2005, Sitch et al., this issue).

The residence time of soil C is sensitive to the nature of the accumulated organic matter. For example, lignin-rich woody carbon is generally less labile than C in tissues derived from herbaceous plants. This lability is to some extent defined by the differences in the C:N ratio of the accumulated plant matter. The potential also exists for priming more efficient C remineralization due to root exudation of specific compounds (Pascual et al. 1998, Kuzyakov 2002). The nature of the organic carbon will also determine the residence time within the C store. Mosses and lichens are non-woody but are more recalcitrant than many vascular plant leaves (Hobbie et al. 2000). Low molecular weight compounds generally have the shortest residence times. If not volatile, they can be physically transported in leachates as dissolved organic matter or consumed by heterotrophs. Over time, more labile moieties (e.g. aliphatic, carboxyl and amide groups) of higher molecular weight compounds are remineralized biologically leaving more recalcitrant polyaromatic compounds which are less likely to be metabolized.

Substantial information is available from *in situ* environmental manipulation experiments on the effects of environmental change drivers on above-ground vegetation (see e.g. Arft et al. 1999, Wahren et al., 2005, Henry et al. 2006) but this is rarely supported by equivalent emphasis on below-ground processes, or on the quantity and quality of soil C stores. Indeed there is little direct experimental evidence of the effects of environmental change on soil C pools, although many studies have noted the likely cascade effects of changes in vegetation community structure on the inputs of organic matter to soils (Hobbie 1996, Aerts 1997, Hobbie et al. 2000, Shaver et al. 2000, Wahren et al., 2005, Henry et al. 2006). The study by Mack et al. (2004) is an exception, however, reporting the effects of 20 years of nutrient additions (10g N and 5g P m^{-2} y^{-1}) on above- and below-ground C storage in Alaskan tundra. The objective of the nutrient additions was to determine the implications of greater mineral nutrient availability (thought to be a likely outcome of soil warming) on above and below-ground C stores. The results revealed that decomposition was stimulated more than plant production, leading to a substantial net loss of C from soils to the atmosphere. These authors suggested that a new conceptual model is needed of the potential responses of tundra to warming, in which decomposition is substantially more sensitive to warming than production. Whether or not the nutrient addition treatment adequately simulated the impacts of climate change can, however, be vigorously debated. In another *in situ* environmental manipulation experiment, using ITEX open-topped chambers (OTCs: see Arft et al. 1999) to simulating warming across the forest (mountain birch)-tundra ecotone in Scandinavia, Sjögersten et al. (2003) used solid-state ^{13}C nuclear magnetic resonance (CPMAS ^{13}C NMR) to characterise functional compound classes of soil organic matter (e.g. alkyl groups, aromatics, phenolics and carboxyls), and whether changes could be detected after two years of treatments. Although the study suggested the soil organic matter was highly labile in these systems (particularly in tundra heaths), there was no evidence of an OTC effect. It was noted, however, that the short duration of the study, together with limited soil warming, would make direct warming effects unlikely. Clearly there is considerable scope to expand investigations of the effects of *in situ* environmental manipulations on the quantity and properties of soil C reservoirs, but the longevity of the studies is a key issue, together with the validity of the treatments for simulating environmental change.

Carbon storage is also sensitive to disturbance. Increased population densities of herbivores, for example, could reduce the carbon store available for accumulation into the soil. In turn, the alteration of soil structure can affect the residence time of carbon in accumulated plant matter. Other disturbance effects, such as fire, flooding, thermokarst and coastal erosion, will also likely reduce terrestrial carbon storage (Robinson and Moore 2000) although some thermokarst erosion events can increase productivity under wet conditions tending to increase net C uptake rates independent of the loss of stored C in connection with physical erosion.

Fire catastrophically redistributes carbon from organic soils to the atmosphere in a variety of forms. Flooding will increase the residence time of the carbon stored in the soil by reducing decomposition rates but photosynthesis may also be reduced. Thermokarst processes can physically expose previously buried, frozen and relatively labile organic soils to the atmosphere allowing aerobic and anaerobic decomposition. Thawing of permafrost in Siberia has been shown to expose very old (Pleistocene) carbon deposits to decomposition in anaerobic lake sediments resulting in significant CH_4 emissions (Zimov et al., 1997).

Synthesis of flux observations

Geographical area and data selection

The area identified as subject for the current synthesis uses a flexible definition of the Arctic such as adopted by the ACIA (Figure 1). Our focus is on the geographical Arctic i.e. the circumpolar north and in particular land areas influenced by the partial or full presence of permafrost.

This area covers the vast majority of the Arctic climatic region, defined as having a mean air temperature of the warmest month (usually July) below 10 ºC. Permafrost is in theory stable when mean annual air temperature is below 0 ºC (Figure 1) but there are documented many exceptions from this rule. In Eurasia and Scandinavia the tree line in most regions is north of the Arctic Circle and in North America at or south of the Arctic Circle.

A major problem with comparability arises when trying to interpolate the available data on fluxes of CO_2 and CH_4 from the circumpolar Arctic. Most flux studies have used static chamber techniques, which provide a snapshot of the flux with a well-defined surface of usually less than $1m^2$ (Table 2). Chamber measurements can be difficult to extrapolate to landscape or regional areas due to fine scale natural local variability in vegetation habitats, moisture and temperature that drive differences in the gas exchange across the landscape. Because of the limited spatial area and the temporal infrequency of the sampling, these measurements are difficult to compare and not easily converted into an annual landscape flux. Most chamber measurements are carried out during a growing season of variable length (depending on latitude, elevation and climate), and replicate measurements are often made for only part of this season (Table 2). These measurements allow the determination of small scale spatial variability in a given area and time but they are less suited for defining the temporal variability of fluxes of the same area over time. Different measurements techniques for chambers have been shown to give different results in the order of 20% (Pumpanen et al. 2004, Widen and Lindroth 2003), which adds to the uncertainty. Extrapolating of component fluxes to landscape- or regional level using algorithms developed from chamber or EC based CO_2 flux measurements have shown some promising results during the growing season (e.g. Groendahl et al., submitted, Oechel et al 2000, Soegaard et al., 2000).

Larger scale fluxes (hectares to km^2) can be obtained from the more expensive eddy covariance flux tower systems, but in the Arctic these measurements are relatively scarce. Only a handful of eddy towers are functioning in arctic tundra. Very few towers function during the winter, primarily as a result of technological challenges associated with remote power generation and supply, icing of instrumentation and falling snow. In order to overcome temporal differences in the measurement period between sites, daily fluxes from different sites and ecosystem types are commonly classified into categories depending on the time of year when the measurements were carried out (summer, fall, winter and spring) and divided into coarse ecosystem categories (wet and dry/mesic ecosystems). This approach can introduce uncertainty in site inter-comparison and synthesis. For example, the summer season in sub-arctic Scandinavia is generally longer than that experienced in northern Greenland and northern Eurasia, which if not accounted for in conversions to annual fluxes and could influence site inter-comparisons. Furthermore, what may be regarded as a relatively dry ecosystem type in a humid region (in e.g. Northern Finland) can in some cases be comparable to a wet ecosystem type in a dry region as e.g. Northern Alaska. Similarly with most plot level studies, it is important that studies provide metrics such as biomass, NDVI, species or functional type cover and abundance and other site specific characteristics to enhance the capacity for inter-study comparisons. Thus in Table 3 we have only included data from studies and years where the mean seasonal fluxes appear to be truly comparable. Annual budgets are available from only a handful of sites (Figure 5). The determining factors for the outcome of any given site and year's annual C budget will be discussed below.

Seasonal fluxes

As mentioned above, fluxes measured at different sites and times may often be difficult to compare. However, both some striking similarities and dissimilarities at large spatial scales appear when comparing regional to continental scale syntheses of available flux data obtained using both eddy correlation and chamber techniques. Table 3 shows a comprehensive compilation of observed mean daily and seasonal/annual NEE and CH_4 fluxes. In this compilation, observations of wet tundra mean summertime NEE for N America, Greenland, N Europe and N Eurasia are similar and in the range -0.5 to -1.5 g C m^{-2} day^{-1} with no clear difference between these regions. Conversely, observations of summertime NEE for dry/mesic tundra differ substantially. Uptake rates in North America, Greenland and N Europe, however, are of the same magnitude as those reported for wet tundra in north-eastern European Russia; i.e. approximately -0.3 and -1 g m^{-2} day^{-1}. The latter could be a result of non standardized site descriptions, which may otherwise be explained through scaling of site dryness using soil moisture or NDVI for example.

Wintertime flux measurements normally show constant but small effluxes relative to summer time measurements but there is some variability between sites for which winter fluxes are available. It is extremely difficult to determine comparable mean fluxes from the critical shoulder periods (see below) and these are purposely not reported in Table 3 other than where they are included in annual estimates. Further research is needed to ascertain any degree of similarity in shoulder season fluxes between land cover types and regions in the Arctic.

Observed summertime wet tundra CH_4 fluxes show a remarkable similarity between regions (Table 3). Seasonal mean emission rates of 15-75 mg CH_4–C m^{-2} d^{-1} are generally found in wet tundra ecosystems and where the water table is close to or at the soil surface the variation is primarily a function of temperature and plant species composition (Christensen et al., 2003). Mesic tundra CH_4 fluxes show a relative larger variation in that here the water table fluctuations and the balance that follows between methane production and oxidation (Figure 2) will be of pivotal importance for the net emission. Hence, mesic tundra fluxes can vary from almost no emission to more than 20 mg CH_4–C m^{-2} d^{-1}. In dry tundra and heath ecosystems in the Arctic and Subarctic methane is frequently being consumed in the soils that therefore is acting as a net sink for atmospheric CH_4 (Whalen and Reeburgh 1990, Sjögersten and Wookey 2002a) at rates generally found below -2 mg CH_4–C m^{-2} d^{-1}. In carbon terms this is a very minor component to the ecosystem atmosphere exchanges but it may be important for the balance of radiative forcing from these dry ecosystems.

Seasonal dynamics and importance for annual budgets

Figures 6 illustrates critical components controlling the seasonal dynamics of C exchange in a simplified arctic tundra ecosystem. Within the four seasons (I-IV in Figure 6) there are important, and at times very different, processes acting which are resulting in the net effect of the individual seasons on the annual budget. Critical facets of early-season conditions - such as a substantial C loss during spring melt and early summer due to release of trapped CO_2, and possibly a hindered onset of photosynthesis due to dry early summer conditions - can seriously affect the annual budget. In midsummer again water deficit can be important as a limiting factor for photosynthesis, while a very warm summer has the potential to stimulate respiration (including root respiration) more than photosynthesis (in particular in dry years) so these effects together can be very important for the annual budget (Crawford et al. 1993, Cooper 2004, Marchand et al. 2005, Kwon et al., in press). In the third season, a mild autumn followed by the delayed appearance of a consistent snowcover could be critical for processes involved in C fluxes. Usually photosynthesis will decline regardless of warm "Indian" summer conditions that will on the other hand stimulate respiration for as long as the soils remain unfrozen (or contain free water). So a mild autumn may also be a very important triggering factor for C losses on an annual basis (Friborg et al. in prep.).

The critical factors for determining the annual carbon budget of a simplified arctic tundra are summarised in Figure 6, which includes examples of factors that can affect seasonal processes (δ_a, δ_b, δ_c, δ_d) occurring in season I (spring), II (summer), III (autumn) and IV (winter) and, therefore estimation of annual budgets. The annual budget can then be summarised as Equation 1 (below) where *k* is a site specific productivity factor and δ represents seasonal factors that indicate the positive or negative effects that each season is having on the net annual balance.

(1) $C_{annual} = k * (\delta_a + \delta_b + \delta_c + \delta_d)$

Importantly, there may be several complications associated with this very simplified model. For example, an early freeze-up in season III, which would tend to increase net C uptake in a given year through preventing respiratory C losses in a lengthy autumn, may act very differently during the subsequent year depending upon whether or not the soil is underlain by permafrost. In a permafrost free setting, where there are still unfrozen conditions and substantial microbial activity beneath the freezing front, there is the chance for a substantial winter-time build-up of CO_2 below the frozen ice and soil layer, which in turn may affect the δ_a in the subsequent year through a substantial and potentially pulsed release of trapped CO_2. In continuous permafrost this hand-over effect from one year to the next may be less apparent.

Nonetheless, Equation 1 may be useful for comparing annual budgets between ecosystems, studies and sites to determine factors controlling not only intra-site inter-annual variability but also for comparing why different sites appear with different annual budgets. The discussion on estimates of annual fluxes below rationalizes why such differences in annual budgets can be found both within and between sites.

Annual estimates

Due to the natural interannual variability determined by the factors discussed above it is extremely difficult to ascertain the C budget status of any tundra ecosystem from single year or even 2-3 year studies. The degree of variability between years is generally quite high. The longest series of annual C balance estimates for tundra ecosystems is from N Alaska, where chamber flux measurements in the 1970's and 1980's, and eddy correlation measurements in more recent years, have indicated a shift from sink to source by the early 1990's, after which there was a tendency for the system to tend towards sink status despite remaining a net source (Oechel et al., 2001). Regardless of these rather dramatic fluctuations in annual budgets over decadal time scales, tundra sites in northern Alaska have also shown relatively stable summertime uptake rates of 40 to 70 g C m^{-2} $season^{-1}$ (Spring to Fall) in recent years (Kwon et al., in press), emphasising the importance of the shoulder season for determining the variability between years.

Other sites where full annual budgets have been monitored include Stordalen in northern Sweden (Friborg et al., in prep.) and Kaamanen in northern Finland (Aurela et al., 2001). From NE Greenland there are several years of full seasonal flux observations available both from wet tundra fen and dry heath sites and annual budgets have been estimated at an overall balance close to zero (Soegaard et al., 2000, Nordstroem et al., 2001). Recently an annual sink estimate of 38 g C m^{-2} $year^{-1}$ was measured in tussock tundra in NE Siberia (Corradi et al., 2005).

The status of C exchange in the circumpolar north based on the few actually observed annual C budgets indicate that Arctic terrestrial ecosystems are functioning with significant spatial and temporal heterogeneity with some regions being sources of carbon to the atmosphere (mostly dry and mesic ecosystems) and some regions sinks (mostly wet tundra) (Figure 5).

From the available circumpolar data it is very difficult to provide a straight answer to the question of whether the Arctic tundra is a source or a sink of atmospheric carbon. There was until recently a tendency for the studies and sites that represented the larger areas of tundra to show source activity (northern Alaska and European Russia, Figure 5) but this pattern has changed since the vast NE Siberian tundra has become represented by Corradi et al.'s (2005) study (Figure 5). Taking into account the error bars also shown in Figure 5 it is impossible, given the currently available measured annual carbon budgets, to say for certain that the overall carbon balance of the circumpolar North should be different from being in equilibrium.

Greenhouse gas budgeting

Few of the annual budgets referred to above include observations of CH_4 emissions. Where such combined measurements are available on an annual basis, i.e. at Stordalen (Sweden), Kaamanen (Finland) and Kolyma (NE Siberia), the contribution of CH_4 to the actual net annual carbon exchanges (NEP, Figure 2) amounts to 10-25% of the heterotrophic respiration (Friborg et al. in prep, Corradi et al., 2005).

Since CH_4 is a greenhouse gas with a radiative forcing potential 23 times greater (expressed as gram per gram) than that of CO_2 (in a 100 yr time perspective), the emissions of methane from wet tundra ecosystems, in particular, must be taken into account in any attempt to document the radiative forcing capacity of arctic landscapes (Johansson et al. submitted). For tundra ecosystems where a third commonly studied greenhouse gas, nitrous oxide (N_2O), is assumed to be rarely exchanged with the atmosphere due to nutrient limitations, estimates of total greenhouse gas fluxes are usually confined to the combined effects of CO_2 and CH_4 exchange. Here a complicating factor is time. Most tundra ecosystems have accumulated carbon over many thousands of years. Over such a period the accumulated and reduced radiative forcing potential of CO_2 uptake is a stronger factor than that of accumulated CH_4 emissions (Frolking et al. in press). However, in most greenhouse gas budgets, focus is generally directed to the immediate emissions and possible changes that may occur and what impact these will have on climate as this responds to change over the coming decades. Over decadal time scales, most wet tundra CH_4 emissions will be a stronger greenhouse forcing factor acting on climate than the CO_2 uptake. Typical calculations of such a total GHG budget may look like that illustrated in Figure 7, which has been derived for the Zackenberg eddy tower site in NE Greenland by applying two typical CH_4 greenhouse warming potential of 63 for a 20 yr time perspective and 23 for a 100 yr time perspective respectively (Friborg et al. 2004, ACIA 2005).

Considering that a) many dry/mesic tundra ecosystems have minimal CH_4 emissions, if any, and CO_2 budgets that are balanced around zero or are actual sources of C to the atmosphere, and b) wet tundra ecosystems are likely to be sources of climate warming over the next few decades due to strong CH_4 emissions; we conclude that arctic tundra regions should currently be considered a net contributor to greenhouse warming. Whether this source functioning will continue into the future without acclimation is uncertain. In all likelihood, this may depend on the response of permafrost that appears to be warming, soil moisture status that appears to be variable with moisture levels increasing in some regions and drying in other regions. A further factor is the future state and carbon fixing potential of the High Arctic.

Current research infrastructure, monitoring and international and scientific coordination will not be sufficient to answer such questions. To further understand the significance of arctic environmental change for global greenhouse warming potential, new, and concerted efforts need to be sustained to investigate further and adequately measure processes modulating C flux in arctic tundra and how C fluxes in arctic landscapes vary across multiple scales of space and time. It is only with these new capacities, can we hope more conclusively to be able to answer the question "*What is the current status of carbon exchange in the circumpolar North*?"

Conclusions

Throughout the Holocene, most tundra in the Arctic has been a net sink for carbon due to low rates of decomposition and loss relative to rates of uptake. Based on the few actually observed annual carbon budgets in the circumpolar north, the current status of carbon exchanges indicates that Arctic terrestrial ecosystems are dynamic and heterogeneous, with some regions being sources of carbon to the atmosphere (mostly dry and mesic ecosystems) and some regions being sinks (mostly wet tundra). If the measurements from sites in N America and North Eurasia are assumed representative for these vast regions, then source and sink areas are roughly balanced. Current global and regional climate modelling of predicted future states of arctic precipitation dynamics and hydrological balance are highly uncertain (ACIA, 2005). The models must be better parameterized and validated in order to constrain predictions of future soil hydrological states that will determine the magnitude and of C efflux from arctic tundra the dynamics and the composition (CO_2, CH_4, VOCs etc.) of that exchange.

Many dry/mesic tundra ecosystems that have minor CH_4 emissions if any, but on the other hand CO_2 budgets that are balanced around zero or are actual sources.Wet tundra ecosystems were most commonly found to be net sinks of C but are likely to enhance radiative forcing over decadal time scales through the emission of CH_4. As such, arctic tundra regions should be concluded to currently be acting as a source of greenhouse warming. Whether this source functioning will continue into the future is uncertain and will depend on the fate of permafrost, soil moisture and surface hydrology and the future state of ecosystem structure and function in the high arctic. To decrease uncertainty and improve our fundamental understanding of carbon balance at high northern latitudes new, novel and concerted research and monitoring efforts need to focused over decadal time scales.

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Table 1. Overview of exogenic and endogenic factors controlling carbon fluxes in the Arctic.

Controls on Carbon flux	**Observed Change or Change Predicted by GCMs and/or Ecosystem Models**	**Relationship with**			**Parameterized in models**	**References**	**Notes**
		uptake	**Loss**	**storage**			
Drivers							
Exogenic							5
Air temperature	Increase	+		+	Yes	IPCC (2001)	
Soil temperature	Increase		+	-		Oechel et al. 1995, Sjögersten and Wookey 2002b, Christensen et al, 2003b	
Moisture availability	Decrease	+	+/-	+	Yes	IPCC 2001, Flannigan and Veum 1974.	
Radiation/Cloud cover		+		-	Yes	Wang and Key 2003	
Nutrient availability	Increase	+	+	+	Some models	Neftel et al. 1985, Laj et al. 1992, Baddeley et al. 1994, Hobbie et al. 2002, Shaver and Chapin 1995.	
Water table			+/-	+		Oberbauer et al. 1996, Oechel et al. 1995	
Active layer	Increase		+	-		Grogan and Chapin 2000	
UV-B	Increase	-			No	Zepp et al. 2003, Niemi et al. 2002, Taalas et al. 2000	
CO_2 concentration	Increase	+	-		Yes	IPCC 2001	
Atmospheric pressure			+	-		Michaelson et al. 1996	
Endogenic							5
Land cover/Vegetation Change and altered dominance of functional types/species	Increased importance of shrubs and decreased importance of cryptogams (****).	?	?	?	No	Myneni et al. 1997, Sturm et al. 2001, Walker 2000, Aerts 1997, Chapin et al. 1996, Hobbie 1996, Oberbauer et al. 1996, Arft et al. 1999, Malmer et al. 2005.	2

	Soil organic matter quantity, quality, C:N, root exudates, root sloughing		?	?	?	No	Ping et al. 1997, 1998, Michaelson et al. 1996, Marion et al. 1997, Walker et al. 1998, a. Valentini et al. 2000, Giardini and Ryan 2000, Aagren 2000, Liiski et al. 1999, White et al. 2000.	3, 4
	Composition of the decomposer community including mesofauna, microfauna, fungi and bacteria		?	?	?		Oberbauer et al. 1996, Panikov 1997. Jonasson et al. 1999. Schmidt et al. 2002	3
	Adaptation and evolution		?	?	?	No	Oechel et al 2000a	
	Methanotrophy	Unknown - increase if soil moisture stays high, decrease if soil moisture too low or too high	+/-	+/-		No	Whalen and Reeburgh 1990, Mancinelli 1995, Torn and Harte 1996, King 1997, Moosavi and Crill, 1998; Reeburgh et al. 1998, West and Schmidt 1998, Christensen et al. 1999, Sjögersten and Wookey 2002a	
Seasonal factors								
	Winter							
	Snow depth		-	+/-				
	Sub-surface Photosynthesis	Unknown - dependent on density and depth of snow pack and changes in radiation	+	+		No	Crawford 2003, Bertrand and Castonguay 2003	
	Frost damage	Increased frost damage	-	+		No		
	Shoulder season							
	Bud Break	Earlier	+	+		Some	Starr and Oberbauer 2003	1
	Phenology		+	+		No	Arft et al. (1999)	
	Pre-development based on growth and phenology of previous years	Unknown and dependent of functional type/species				No		
	Growing season							

	Growing season length and variability	Increased length and variability	+	+		🟨	
	Timing, rate and depth of thaw	Earlier, quicken, increase	+	+		🟨	
	Thaw front dynamics in relation to nutrient availability and potential for root exploration	🟨	+	+		🟨	
	Distribution of rainfall not amount and effect on cryptogams	Increased variability in rainfall	-	+/-		🟨	(Lloyd 2001a, 2001b, Soegaard et al. 2000)

	No direct effect
🟨	Lacking information
+	Strong positive relationship in the Arctic
-	Strong negative relationship in the Arctic
+/-	Indicates parabolic response or a maximal response under optimal conditions
	(Blank) indicates not directly relevant
?	Relationship unknown and/or has been shown to be positive or negative correlated

Notes	
1	Shoulder seasons are spring/autumn when thaw/freeze-up occurs
2	Implications of and for litter quality and quantity
3	Genetic controls on multiple traits
4	Can also be considered exogenic
5	Change predicted for exogenic drivers easier than for endogenic

Table 2. Standard observational methods for measuring components of ecosystem carbon balance and whether or not the method is useful for direct measurements of component fluxes.

	GEE	NEE	ER	CH_4 Flux	Fixed F'print	Annual Measurements
Static Chamber	Y	Y	Y	Y	Y	Y/N
Eddy tower	N	Y	N	Y	N	Y
Remote Sensing	Y	N	N	N	Y	N

Table 3. A compilation of published data for CO_2 and CH_4 fluxes in the circumpolar North.

CO_2 Flux	**Period**	**Year**	**Geographical position**	**Location**	**Method**	**Ecosystem**	**Reference**
North America							
0.081 gC $m^{-2}d^{-1}$	Annual	1995-1996	69°-70°N 148°53'W	Alaska	EC and CH	Acidic - Tundra landscapes	(Oechel et al. 2000b)
0.043 gC $m^{-2}d^{-1}$	Annual	1995-1996	69°-70°N 148°53'W	Alaska	EC and CH	Non Acidic - Tundra landscapes	(Oechel et al. 2000b)
0.128 gC $m^{-2}d^{-1}$	Annual	1995-1996	69°-70°N 148°53'W	Alaska	EC and CH	Shrub - Tundra landscapes	(Oechel et al. 2000b)
0.002 gC $m^{-2}d^{-1}$	Annual	1995-1996	69°-70°N 148°53'W	Alaska	EC and CH	Wet sedge - Tundra landscapes	(Oechel et al. 2000b)
0.109 gC $m^{-2}d^{-1}$	Annual	1960 – 1998		Alaska	EC and CH	Alaskan ecosystem	(Oechel et al. 2000a)
0.31 gC $m^{-2}d^{-1}$	Annual/ estimate	1993 - 1994	69°-70°N 148°53'W	Alaska	CH	Tundra (Tussock tundra)	(Oechel et al. 1997)
0.07 gC $m^{-2}d^{-1}$	Annual/ estimate	1993 - 1994	69°-70°N 148°53'W	Alaska	CH	Wet sedge	(Oechel et al. 1997)
-0.011 gC $m^{-2}d^{-1}$ (1998) and -0.044 gC $m^{-2}d^{-1}$ (1999)	Annual	1998-1999	71°18'N 156°42'W	Alaska	CH and Model	Tundra (coastal arctic tundra)	(Grant et al. 2003)
0.062 gC $m^{-2}d^{-1}$	Season (winter season 240 days)	1996 - 1997	69°08'N/ 70°23'N 148°30'W/ 149°60'W	Alaska	Snow profile	A wide range of systems	(Fahnestock et al. 1999)
0.064 gC $m^{-2}d^{-1}$	Season (March – May 92 days	1996	68°38'N 149°38'E	Alaska	Snow profile	Moist acidic tundra	(Fahnestock et al. 1998)

-1.1 gC $m^{-2}d^{-1}$ and -0.7 gC $m^{-2}d^{-1}$	spring and summer season 147 days	1999-2000	71°19’N 156°37’W	Alaska	EC	Tundra (wet sedge tundra)	(Harazono et al. 2003)
-0.623 gC $m^{-2}d^{-1}$	growing season (June – August 90 days)	1994 and 1995	69°08’N 148°50’W	Alaska	EC	Tundra (moist-tussock tundra)	(Vourlitis et al. 1999)
-0.529 gC $m^{-2}d^{-1}$	growing season (June – August 81 days)	1994 and 1995	69°08’N 148°50’W	Alaska	EC	Tundra (wet-sedge tundra)	(Vourlitis et al. 1999)
-0.835 gC $m^{-2}d^{-1}$	Season (June – August 92 days)	1995	69°08’N 148°50’W	Alaska	EC	Tundra (wet-sedge tundra)	(Vourlitis et al. 2000)
0.114 g C m^{-2} d^{-1}	Season	1994	68°38’N/ 149°36’W	Toolik, Alaska	EC	Lake	(Eugster et al. 2003)
-70 to -40 g C m^{-2} $season^{-1}$	Season	1999-2003	71° 19' N : 156° 36' W	Barrow, Alaska	EC	Wet sedge	(Kwon et al. Submitted)
-0.15 gC $m^{-2}d^{-1}$ to -0.2 gC $m^{-2}d^{-1}$	Season (June to August) 90 days	1994-1995	70°16’N/ 148°53’W	Alaska	EC	Arctic coastal plain	Vourlitisand Oechel, 1997
-0.1 gC $m^{-2}d^{-1}$	Season (June to August) 77 days	1995	69°56’N/ 148°48’W	Alaska	EC	Arctic coastal plain	Vourlitisand Oechel, 1997
-20 - -34 g C m^{-2} $season^{-1}$	Season	2004-2005	64° 52' N : 111° 34' W	Daring Lake, Canada	EC	Mixed tundra	LaFleur et al. (in prep.)

-0.73 gC m^{-2}d^{-1} to -1.508 gC m^{-2}d^{-1}	Season (June – Sept) 120 days	1999 - 2003	71° N 156° W	Alaska	Aero Dyn	Wet Sedge	Harazono et al. 2003
North Atlantic Area							
-0.0063 gC m^{-2}d^{-1}	Annual estimate	1997	74°28'N 20°34'W	NE Greenland	EC / model	Arctic valley (integrated)	Soegaard et al. 2000
-0.015 gC m^{-2}d^{-1}	Annual estimate	1997	74°28'N 20°34'W	NE Greenland	EC / model	Fen	Nordstroem et al. 2001
-0.8 gC m^{-2}d^{-1}	Season (June – August)	1997	74°28'N 20°34'W	NE Greenland	EC	Arctic valley (integrated)	Soegaard et al. 2000
-1.09 gC m^{-2}d^{-1}	Season (June – August)	2004	74°28'N 20°34'W	NE Greenland	CH	Arctic valley (integrated)	Groendahl et al. Submitted
-0.63 gC m^{-2}d^{-1}	season (June-August)	1997	74°28'N 20°34'W	NE Greenland	CH	Arctic valley	Christensen et al. 2000
-0.047 gC m^{-2}d^{-1} and 0.057 gC m^{-2}d^{-1}	Season (83 days (95)) and 87days (96))	1995 and 1996	79°56'N 11°55'E	Svalbard	EC/model	Desert (subpolar desert)	Lloyd, 2001a;Lloyd, 2001b
-0.0175 gC m^{-2}d^{-1} to -0.291 gC m^{-2}d^{-1}	Season (June-August) 80 days	1997, 2000-2003	74°28'N 20°34'W	NE Greenland	EC	Heath	Groendahl et al. in press; Soegaard et al. 2000
-0.13 gC m^{-2}d^{-1}	season (June – August) 90 days	1997	74°28'N 20°34'W	NE Greenland	EC	Willow	Soegaard et al. 2000
-1.25 gC m^{-2}d^{-1} to -2.196 gC m^{-2}d^{-1}	Season (July-August) 40-56 days	1996-1999	74°28'N 20°34'W	NE Greenland	EC	Fen	Rennermalm et al. 2005; Soegaard et al. 1999

Northern Europe							
-0.036 gC $m^{-2}d^{-1}$ to -0.074 gC $m^{-2}d^{-1}$	Annual	2001-2003	68°21’N 19°02’E	Sweden	EC	Mire (subarctic mire)	Friborg in prep.
-2.04 gC $m^{-2}d^{-1}$	season (June-August) 60 days	1996	69°28’N 27°14’E	Finland	EC	Forrest (Birch ecosystem)	Aurela et al. 2001
-0.0519 gC $m^{-2}d^{-1}$	Annual	1998-1999	69°08’N 27°17’E	Finland	EC	Fen (subarctic flark fen)	Aurela et al. 2002
0.155 gC $m^{-2}d^{-1}$	Winter (Oct – Mar) 186 d	1998 – 1999	69°08’N 27°17’E	Finland	EC	Fen (subarctic flark fen)	Aurela et al. 2002
0.449 gC $m^{-2}d^{-1}$ to -1.53 gC $m^{-2}d^{-1}$	Season (June – September)	1995	69°08’N 27°17’E	Finland	EC and CH	Fen (flark fen)	Heikkinen et al. 2002b
-1.09 gC $m^{-2}d^{-1}$ and -0.92 gC $m^{-2}d^{-1}$	Season (June-September) 93 days	1998 and 1999	69°49’N 27°10’E	Finland	CH	Mire (Palsa mire)	Nykanen et al. 2003
Euroasia							
-0.104 gC $m^{-2}d^{-1}$	Annual	2002-2003	68°37’N 161°21’E	Russia	EC	Tussock tundra	Corradi et al. 2005
-0.12 gC $m^{-2}d^{-1}$	Season (late summer – autumn) 85 days	2000	65°36’N 171°04’E	Russia	EC	Tundra	Zamolodchikov et al. 2003
0.094 gC $m^{-2}d^{-1}$	Season (winter – 248 days)	1993-1998	65 -74°N 63°E-172°W	Russia	CH / model	Tundra landscape	Zamolodchikov et al. 2001

-0.24 gC $m^{-2}d^{-1}$	Season (summer – 117 days)	1993-1998	65 -74°N 63°E-172°W	Russia	CH / model	Tundra landscape	Zamolodchikov et al. 2001
-0.286 gC $m^{-2}d^{-1}$	Season (July – August) 21 days	1995	67°57'N 64°40'E	Russia	CH	Tundra -tall Shrub	Zamolodchikov et al. 2000
0.30 gC $m^{-2}d^{-1}$	Season (June – August) 47 days	1996	67°20'N 64°44'E	Russia	CH	Tundra – Dwarf Shrub (60% of total area)	Zamolodchikov et al. 2000
-0.915 gC $m^{-2}d^{-1}$	Season (June – August) 47 days	1996	67°20'N 64°44'E	Russia	CH	Tundra – Sedge bog	Zamolodchikov et al. 2000
-0.64 gC $m^{-2}d^{-1}$	Season (June – August) 47 days	1996	67°20'N 64°44'E	Russia	CH	Tundra - Shrub	Zamolodchikov et al. 2000
-1.21 gC $m^{-2}d^{-1}$ and 0.75 gC $m^{-2}d^{-1}$	Season (June – September) 90 days	2001	67°23'N 63°22'E	Russia	CH	Tundra (wet) and Tundra (dry)	Heikkinen 2003, Heikkinen et al. 2004,
-0.94 gC $m^{-2}d^{-1}$ to 1.8 gC $m^{-2}d^{-1}$	Season (June – August) 77 days	1999	67°23'N 63°22'E	Russia	CH	Tundra – wetlands and shrub	Heikkinen et al. 2002a

CH_4 Flux	Period	Year	Geographical position	Location	Method	Ecosystem	Reference
North America							
0.073 gC $m^{-2}d^{-1}$ (wet) 0.019 gC $m^{-2}d^{-1}$ (mesic)	Season (June-Aug)	1991-1992	68°38'N 149°38'W	Toolik Lake Alaska	CH	Wet sedge and mesic tussock tundra	Christensen 1993.
0.063 gC $m^{-2}d^{-1}$ (1998) 0.055 gC $m^{-2}d^{-1}$ (1999)	Annual	1999	71°18'N 156°42'W	Alaska	CH and Model	Tundra (coastal arctic tundra)	Grant el al. 2003
0.016 gC $m^{-2}d^{-1}$ to 0.0515 gC $m^{-2}d^{-1}$	Season (June – Sept) 120 days	1999 - 2003	71° N 156° W	Alaska	CH	Wet Sedge	Harazono et al. 2003
North Atlantic Area							
0.0324 gC $m^{-2}d^{-1}$	season (June – august) 86 d.	1997	74°28'N 20°34'W	NE Greenland	EC	Fen	Friborg et al. 2000
0.0341 gC $m^{-2}d^{-1}$	season (June-August)	1997	74°28'N 20°34'W	NE Greenland	CH	Integrated Arctic valley(wet)	Christensen et al. 2000
Northern Europe							
0.0139 gC $m^{-2}d^{-1}$	Annual Campaigns	2001-2002	68°21'N 19°02'E	Sweden	EC	Mire (subarctic mire)	Friborg et al. in prep.
0.091 gC $m^{-2}d^{-1}$ (1998) to 0.133 gC $m^{-2}d^{-1}$ (1999)	Season (July - Oct) 90 days	1998 - 1999	69°49'N 27°10'E	Finland	CH	Mire (Palsa mire)	Nykanen et al. 2003
0.001946 gC $m^{-2}d^{-1}$ to 0.0168 gC $m^{-2}d^{-1}$	daily (May)	1996	68°21'N 19°02'E	Sweden	EC and CH	Mire (subarctic mire)	Friborg et al. 1997

0.0112 gC $m^{-2}d^{-1}$	Season (May to October)	1995 1997 1998	69°8'N 27°16'E	Finland	EC	Mire (aapa mire)	Hargreaves et al. 2001
Euroasia							
0.0017 gC $m^{-2}d^{-1}$ (2.3 mg CH_4 m^{-2} $d^{-1)}$	Summer	1994	67-77 °N	Russia	CH	Mesic	Christensen et al. 1999
0.035 gC $m^{-2}d^{-1}$ (46.8 mg CH_4 m^{-2} $d^{-1\,)}$	Summer	1994	67-77 °N	Russia	CH	Wet	Christensen et al. 1999
10 g CH_4 m^{-2} $season^{-1}$ and 0.05 g CH_4 m^{-2} $season^{-1}$ or 0.111 g CH_4 m^{-2} d^{-1} and 0.0006 g CH_4 m^{-2} d^{-1}	Season (June – September) 90 days	2001	67°23'N 63°22'E	Russia	CH	Tundra(wet) and Tundra (dry)	Heikkinen 2003. Heikkinen et al. 2004

Figure 1.

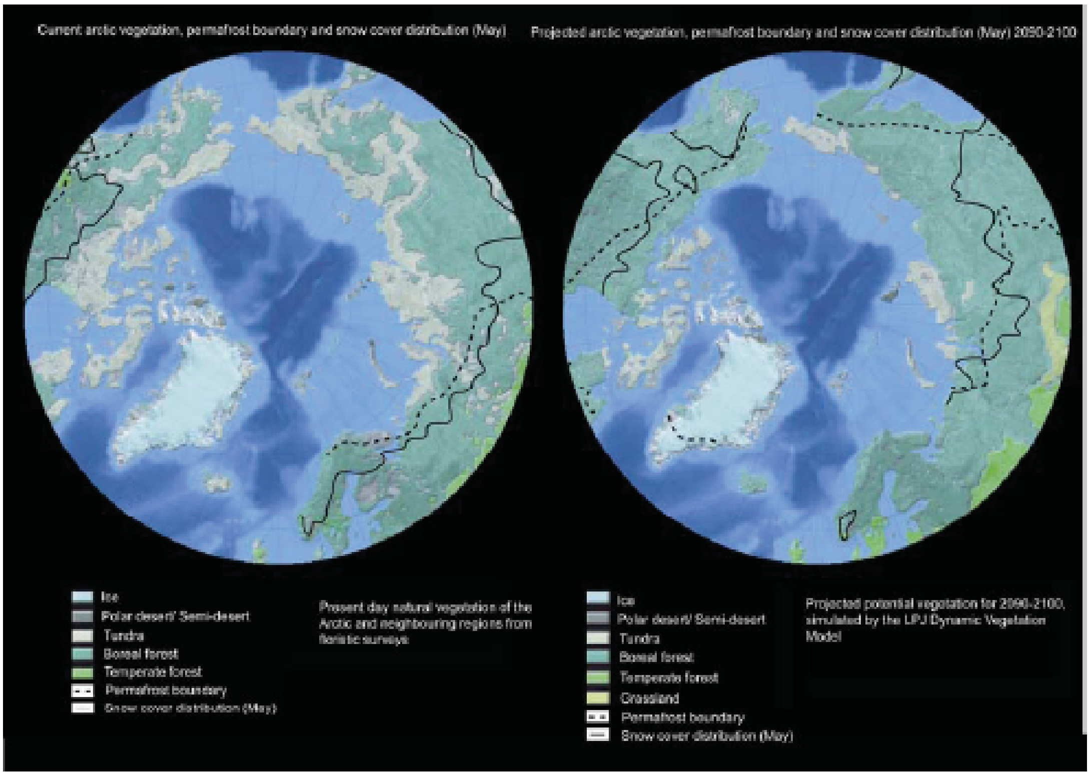


Figure 1. Map of the circumpolar north showing current and predicted vegetation distribution as well as permafrost and snow cover distribution (modified from ACIA, 2005)

Figure 2.

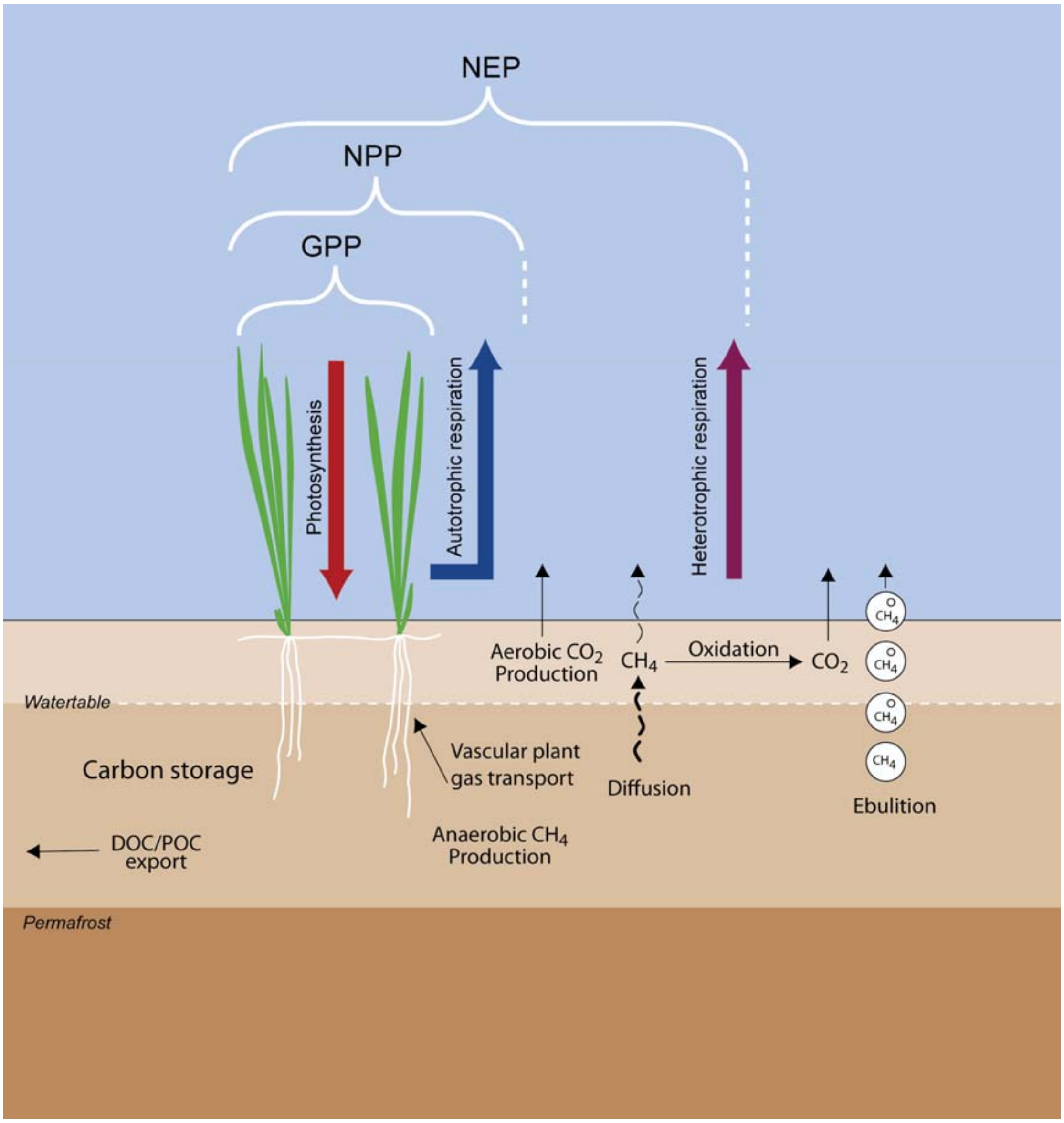


Figure 2. Schematic diagram of the processes governing the net balance of CO_2 and CH_4 fluxes in typical tundra settings.

Figure 3.

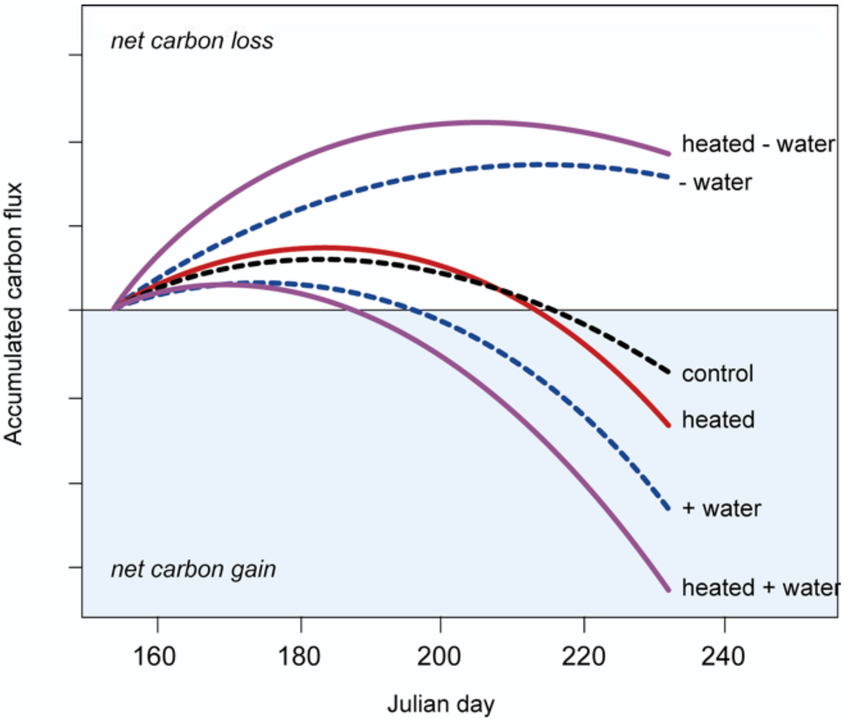


Figure 3. Schematic conceptual illustration of growing season accumulated fluxes in a tundra ecosystem subject to experimental manipulations of temperature and moisture. Soil moisture conditions are seen to be a key for the resulting net flux. This schematic is based on modelled results by Huemmrich et al. (in prep.).

Figure 4.

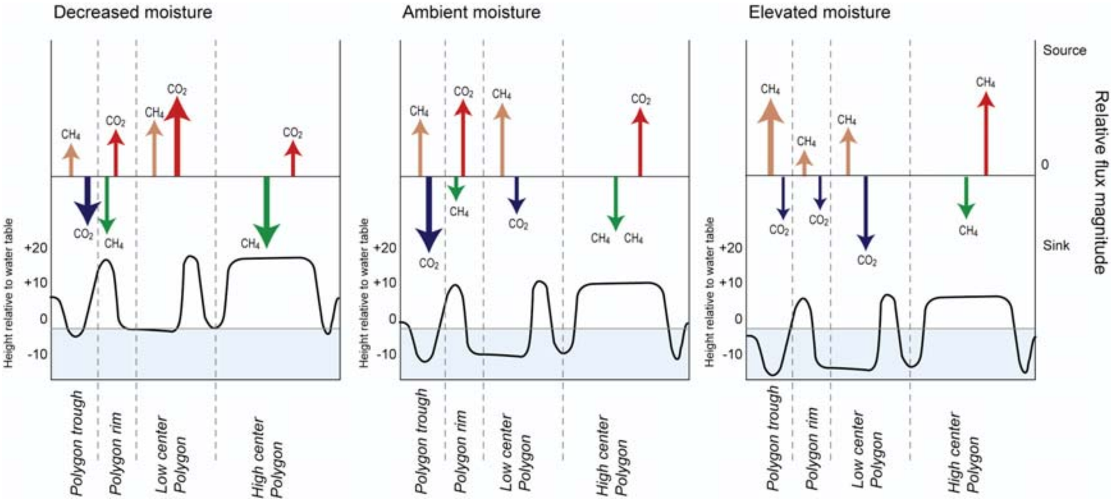


Figure 4. Schematic illustration of variation in water table and how it affects CO_2 and CH_4 dynamics in a complex polygon tundra terrain. The black line in the lower panels indicate the soil surface. The same change in soil moisture can differentially affect the magnitude and even sign of CO_2 and CH_4 fluxes depending on the microtopography. Solid arrows indicate the greatest source and sink activity for CO_2 and CH_4 under each of the moisture conditions.

Figure 5.

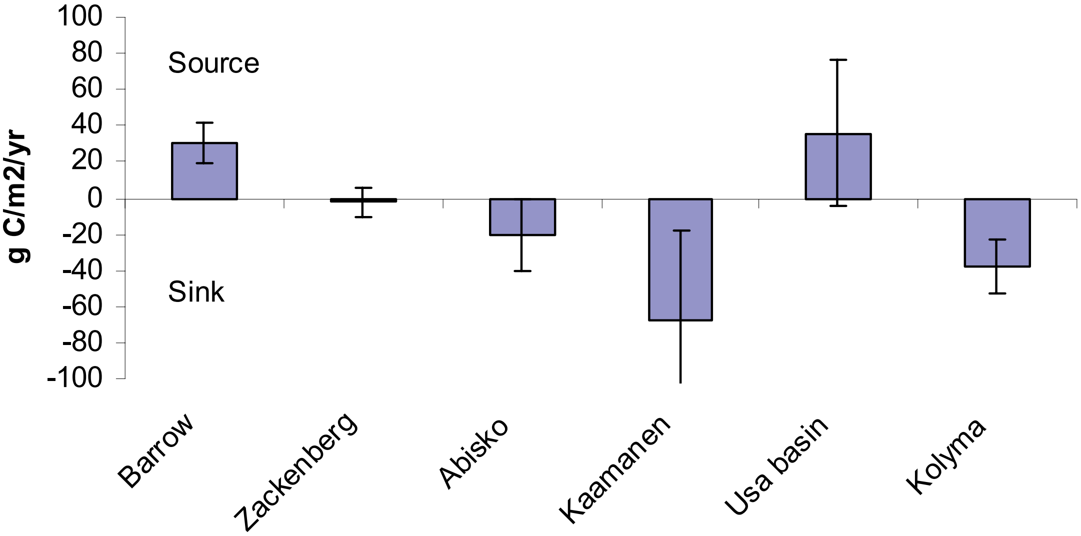
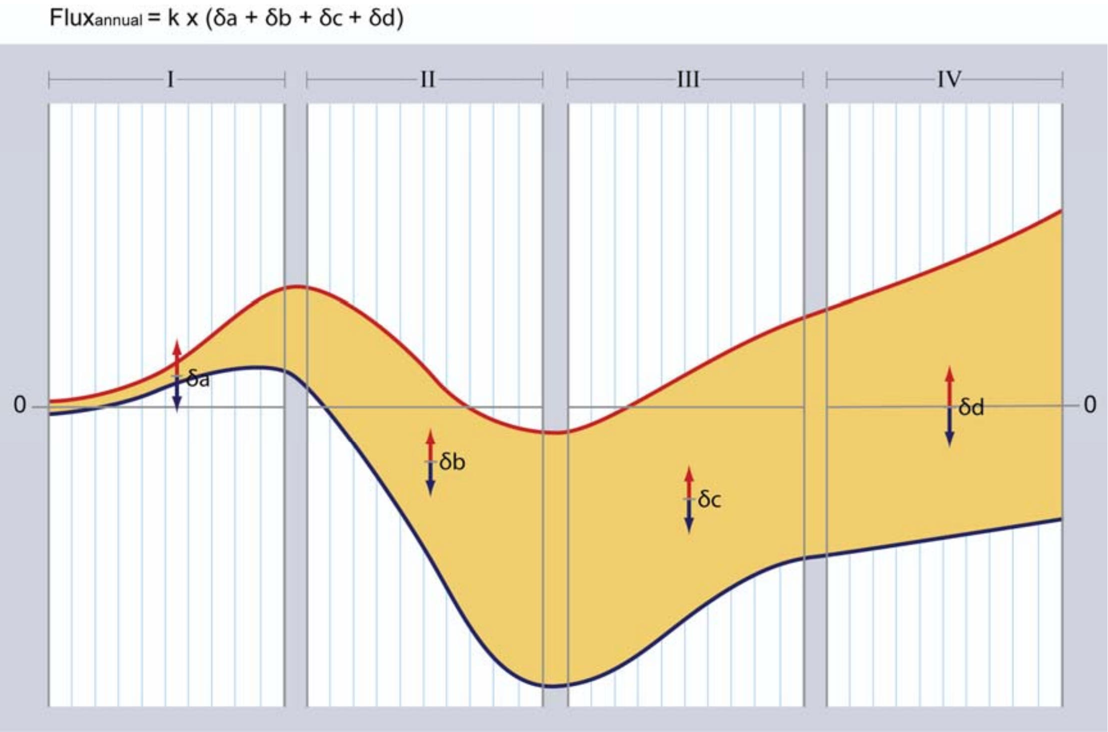


Figure 5. A compilation of annual budgets based on measurements at sites ranging from Alaska over Greenland, northern Scandinavia and north-eastern European Russia to NE Siberia. Data from Oechel et al. 2000; Nordstroem et al., 2001; Soegaard et al., 2000; Christensen et al., 2000; Aurila et al. 2001; Friborg et al. in prep.; Heikkinen et al., 2003 and Corradi et al., 2005.

Figure 6.



Examples of requirements for δx to be:

	δa	δb	δc	Δd
Positive	I short (little snow); Soil moisture limitations; Lots of trapped CO_2	II short and warm. Moisture limitations on GPP; Insect outbreaks.	III long and dry	IV (snowcover) long
Negative	I long and cold; Little trapped CO_2	II long and cold. No moisture deficit for GPP	III short; Early freeze-up	IV (snowcover) short

Figure 6. Conceptual model for the seasonal dynamics of accumulated carbon exchange with the atmosphere in a tundra ecosystem. The four different seasons determining the annual balance are indicated starting with the Spring (I) defined as the time from snowmelt until the carbon balance turns negative. The reverse point defines the end of the following period defined as Summer (II). Autumn is from the turning point of the carbon balance to the onset of permanent snowcover (III) and winter is the permanent snow covered period (IV). Examples of critical parameters for the annual total budget outcome in these individual parts of the season are shown in the inserted table.

Figure 7.

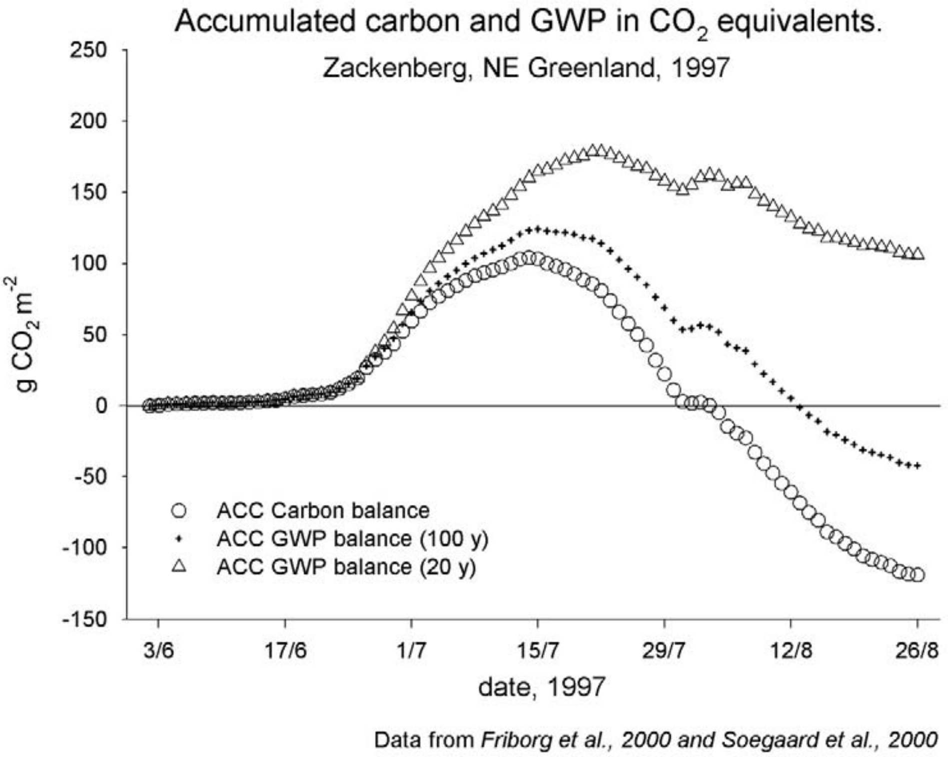


Figure 7. An accumulated greenhouse gas budget (CO_2 and CH_4 as CO_2 equivalents) for a northern wet tundra site versus one of CO_2 only (from ACIA, 2005 based on data in Soegaard et al. 2000 and Friborg et al. 2000).

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The thesis provides an analysis of the exchange of CO_2 between the atmosphere and the vegetation communities in the High Arctic at different temporal and spatial scales. Using a time series of data from a dry heath ecosystem in Zackenberg NE Greenland, it was shown that timing of snowmelt and temperature in the growing season strongly control the interannual variability in ecosystem CO_2 uptake rates. The area has during the past years experienced a warming during the summer season, which was shown to increase the uptake of CO_2 by the vegetation. The increasing earlier snowmelt prolonged the length of the growing season, which in combination with high temperatures increased uptake rates. The dry heath ecosystem in general gained carbon during the summer season in the order of magnitude -1.4 gCm^{-2} up to 32 gCm^{-2}. This result is filling out a gap of knowledge on the response of high Arctic ecosystems to increased warming in the region. A cross scale analysis of eddy covariance and chamber data showed a good agreement between the two methods, which lead to an estimate of CO_2 exchange based on NDVI. A timeseries of satellite imagery for the 2004 growing season provided the opportunity to upscale fluxes from the measurements conducted in the valley to a regional level. Including information on temporal and spatial variability in air temperature and radiation, together with NDVI and a vegetation map a regional estimate of the CO_2 exchange during the summer was provided, elaborating the NDVI based estimate on net carbon exchange.

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