Climate warming and permafrost thaw may lead to increased emissions of greenhouse gases from northern tundra soils. In this work, fluxes of carbon dioxide, methane and nitrous oxide were studied in a subarctic tundra ecosystem. Fluxes were verified at the landscape level by comparing the results of two independent methods and then scaled up over a larger region. The results demonstrate the large heterogeneity of subarctic tundra environment with respect to the greenhouse gas fluxes. Also, a strong, previously unknown source of nitrous oxide is revealed.
MAIJA E. MARUSHCHAK

Carbon Dioxide, Methane and Nitrous Oxide Balance of Subarctic Tundra from Plot to Regional Scales

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ABSTRACT:

At present, the northern tundra biome acts as a sink of carbon dioxide (CO₂) and a source of methane (CH₄). In the future, warming and associated permafrost thaw may increase the release of greenhouse gases from tundra soils to the atmosphere, which would be a positive feedback for the climate warming. At the same time, warmer temperatures may lead to increased C sink in the arctic vegetation. Despite the increased attention on tundra gas exchange during the recent years, there are still large uncertainties even concerning the present day greenhouse gas balance.

The aim of this work was to determine the regional CO₂, CH₄ and nitrous oxide (N₂O) balance and total radiative impact of a subarctic tundra landscape on an annual basis. The most of the data was collected at a site located on discontinuous permafrost zone in Northeast European Russia (67°03’N, 62°57’E, 100 m a.s.l.). Fluxes were measured at the plot scale with chamber and gas gradient techniques on all important land cover types and spatially extrapolated over a region of 98.6 km² using high-resolution satellite data. The spatially extrapolated plot scale fluxes were verified at landscape scale against eddy covariance measurements of CO₂ and CH₄ before upscaling to the regional level.

On an annual basis the study region acted as a net CO₂ sink of 41 ± 57 g C m⁻², a CH₄ source of 5.0 ± 1.3 g C m⁻² and a N₂O source of 5.8 ± 7.1 mg N m⁻². When expressed as CO₂-equivalents over a 100-year time horizon this sums up to a total regional climate forcing of 20 ± 214 g CO₂-eq m⁻², meaning a neutral impact on the climate during that year. Leaf area index of vascular plants explained well the large spatial variability observed in the CO₂ fluxes across the landscape, and also correlated positively with CH₄ emissions from tundra wetlands: willow stands and fens. These wetland types were responsible for 99% of the regional CH₄ release. Measurements of N₂O fluxes at the main study site and Finnish palsa mires revealed a previously unknown, strong source of this gas: bare peat surfaces on permafrost peatlands that are created by physical processes related with harsh climate. The other land cover types showed negligible N₂O release, which is in line with previous studies in high-latitude ecosystems. The high emissions from bare peat resulted from a combination of factors favouring both nitrification and denitrification: low C:N ratio of peat, lack of vegetation and intermediate moisture content.

The heterogeneity in gas exchange across subarctic terrain observed in this study stresses the great importance of accurate spatial extrapolation for producing meaningful regional flux estimates. Due to the large variability between the land cover types, the long-term climate change response of GHG balance will be largely determined by changes in the landscape composition. For example, the relative coverage of peat plateaus vs. wet peatlands, determined by permafrost distribution, is important since these peatland types have contrasting fluxes with respect to all the three GHGs.

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CAB Thesaurus: greenhouse gases; carbon dioxide; methane; nitrous oxide; cold zones; permafrost; tundra; wetlands; peatlands; leaf area index; spatial variation; gas exchange; climatic change
TIIVISTELMÄ (ABSTRACT IN FINNISH):

Pohjoisen tundra-alue toimii nykyisin hiilidioksidin (CO₂) nieluna ja metaanin (CH₃) lähteenä. Tulevaisuudessa ilmaston lämpenemisen ja ikiroudan sulamisen myötä kasvihuonekaasujen vapautuminen tundran maaperästä voi lisääntyä, millä olisi ilmaston lämpenemistä edelleen kiihdyttävä vaikutus. Toisaalta korkeammat lämpötilat voivat johtaa lisääntyneeseen hiilen sidontaan tundrakasvillisuuteen. Vaikka kiinnostus pohjoisten alueiden kasvihuonekaasuvirtoja kohtaan on lisääntynyt viime vuosina, liittyv tundran tämänhetkiseenkin kasvihuonekaasutaukseeseen suuria epävarmuuksia.

Tämän työn tarkoituksena oli määrittää subarktisen tundra-alueen vuotuinen CO₂, CH₃ ja tiyppioksidsiuuletase (N₂O) sekä säteilypakote. Suurin osa aineistosta kerättiin epäjakulavien ikiroudan vyöhykkeellä Luoteis-Venäjällä sijaitsevalla tutkimusalueella (67°03′N, 62°57′E, 100 m mpy). Kaasuvirtoja mitattiin kammio- ja kaasugradientititeknikoilla kaikista tärkeimmistä maanpeiteyypeistä ja tulokset yleistettiin laajemmalle alueelle korkean resoluution satelliittiaineistoja käytävän. Kaasuvirtojen spatioalainen yleistys tarkistettiin ensin vertaamalla sitä maisematasolla kovariantissimenetelmällä mitattuihin CO₂ ja CH₃ virtoihin, minkä jälkeen se laajennettiin kattamaan koko 98,6 km²:n tutkimusalue.

Vuositasolla tutkimusalue sitoi hiilidioksidia 41 ± 57 g C m⁻² ja päästi metaania 5,0 ± 1,3 g C m⁻² ja tiyppioksidsiuulua 5,8 ± 7,1 mg N m⁻². Hiilidioksidiekvivalentteina ilmaistuna koko tutkimusalueen kumulatiivinen ilmastosakote 100 vuoden tarkastelujaksona oli tutkimuksen tekovuotena 20 ± 214 g CO₂-eq m⁻², mikä tarkoittaa neutraalia vaikutusta ilmastoon. Putkilokasvien lehtialaideksi selittä hyvin CO₂-virrissa havaittua suurta alueellista vaihtelua, ja se korreloisi positiivisesti myös tundrakosteikkojen CH₃-päästöjen kanssa. Kosteikot – lettosot ja pajuot – tuottivat 99 % alueellisesta CH₃-päästöstä. Tiyppioksidsiuuvin mittauksissa venäläisellä tutkimusalueella sekä suomalaisilla palsaosoilla paljastui aiemmin tuntematon, voimakas N₂O:n lähde: ikiroutasoina sijaitsevat paljaat turvepinnat, jotka ovat syntyneet ankaraan ilmastooh liittyyvien fyysikaalisten prosessien tuloksena. Muissa maanpeiteyypeissä ei esiintynyt N₂O-päästöjä, mikä vastaa aiempiä tutkimus tuloksia tundran N₂O-dynamiikasta. Korkeat N₂O-päästöt paljailta turvepinnolta ovat seuraukset erilaisten sekä niitrifikaatiota että dentifrikaatiota suosivien tekijöiden yhteisvaikutuksesta. Näitä tekijöitä ovat turpeen alhainen C:N-suhte, kasvillisuuden puuttuminen ja riittävä, muttei liian suuri kosteuspiirituus.

Tässä tutkimuksessa havaittut suuret alueelliset vaihtelut subarktisen tundran kaasuvirroissa korostavat tarkan spatioalisen yleistyksen tärkeyttä alueellisia kaasutauksia laskettaessa. Koska kasvihuonekaasuvirrat vaihtelevat suuresti maanpeiteyppien välillä, kaasutaukseen vaste ilmastonmuutokseen määriittää pitkällä tähtämällä maanpeiteyppien levineisyydessä tapahtuvien muutosten perusteella. Esimerkiksi ikiroudassa olevien kuivien soiden ja märkien tundrakosteikkojen suhteellisella levineisyydellä on suuri merkitys, sillä näillä suotyyppillä on täysin toisistaan poikkeava kasvihuonekaasudynamikka kaikkin kolmen tässä työssä tutkitun kaasun osalta.
Yleinen suomalainen asiasanasto: kasvihuonekaasut; hiilidioksid; metaani; ilokaasu; subarktinen vyöhyke; ikirota; tundra; suot; alueelliset erot; vaihtelu; ilmastoaiakutukset; ilmastonmuutokset
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When I started to collect data for this thesis I was expecting interesting experiences but still I could have only a very faint idea of what it was going to bring along. Several months of field work in Russian tundra, some weeks in trains there and back, hundreds of kilometers of tundra walk with and without a flux chamber, feeling at home in a tiny green cabin in the middle of nowhere. Meeting people in the field and office, on the road, at project meetings and work-shops, talking science and non-science, getting inspired of different ways of working, thinking and solving problems. Hours and hours spent staring at the computer screen, being excited and frustrated and then again excited by the data, seeing how little pieces of information fit together and you get a glimpse of the big picture. Now when the work has been materialized into this book, seeing only my name on the first page feels unfair. There are many people who have been so important for this piece of work to get done.

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I have been lucky to get a bunch of great people around me to share the everyday ups and downs of doing science. Colleagues in the Biogeochemistry research group and in the CARBO-North community, particularly the wonderful people from Finland, Russia and Denmark with whom I spent time in tundra: thank you! There are many unforgettable moments we have spent together. I want to acknowledge also all the coauthors who participated in preparing the manuscripts included in this thesis. My special thanks go to our department secretaries Kaija Ahonen, Ritva Karhunen and Marja-Leena Patronen, who are able to solve any kind of challenge related to university administration.

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Finally, I thank from my heart my family and friends, who have lived through with me this long process and always shown great interest in what I am doing. Your support has kept me going. I devote this thesis to my husband Igor and our little son Petja. You are the best of the best!

Pori, 18 December 2013.

Maija E. Marushchak
LIST OF ABBREVIATIONS

AL      Active layer depth
EC      Eddy covariance
ER      Ecosystem respiration
GHG     Greenhouse gas
GP      Gross photosynthesis
GWP     Global warming potential
LAI     Leaf area index
LCC     Land-cover classification
NEE     Net ecosystem CO₂ exchange
RF      Radiative forcing
WT      Water table depth
LIST OF THE ORIGINAL PUBLICATIONS

This dissertation is based on the following original publications:


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AUTHOR'S CONTRIBUTION

Chapter 2. The author Maija E Marushchak (née Repo) contributed to the design of the study. She carried the main responsibility for data collection and processing related to the plot scale CO₂ fluxes, and for the data integration between the groups. The author wrote the first version of the manuscript together with Isabell Kiepe and Tarmo Virtanen, after which the other co-authors contributed to the writing process.

Chapter 3. The author contributed to the design of the study. She carried the main responsibility for data collection and processing related to the plot scale CH₄ fluxes, and contributed substantially to writing of the manuscript.

Chapter 4. The author designed the study with Pertti Martikainen and was mainly responsible for data collection and processing. She wrote the first version of the manuscript together with Pertti Martikainen and Christina Biasi, after which the other co-authors contributed to the writing process.

Chapter 5. The author contributed to the study design, and was mainly responsible for data collection and processing, and writing of the manuscript.
1 General introduction

1.1 ARCTIC CARBON AND NITROGEN POOLS

Arctic ecosystems store a huge amount of carbon (C) and nitrogen (N) in their soils. This soil organic matter (SOM) pool has been accumulated in cold and humid conditions that limit decomposition of organic matter. Permafrost regions with soils that remain below 0°C for at least two consecutive years occupy 18.8 million km² of the Northern Hemisphere, 35 % of which is located in Eurasia (Tarnocai et al. 2009), particularly in Russia (Anisimov and Reneva 2006). The C pool in these northern permafrost soils is estimated as 1024 Pg (in 0 to 3 m), which is about 40 % of the global soil C pool (Tarnocai et al. 2009) and more than the C pool in the atmosphere. The available estimate of the tundra N pool by Post et al. (1985), 3.7 Pg, is limited to the upper 1 m and is likely an underestimate. Using the C pool estimate by Tarnocai et al. (2009) and C:N ratio of 20-40 of soil, the size of tundra soil N pool would be 26-51 Pg. As much as 90 % of the high-latitude C pool (Tarnocai et al. 2009) and, similarly, a large part of soil N, is currently in permanently frozen soil layers. These permafrost C and N pools are largely protected from soil microbial activities, but there is a considerable concern that they will become accessible for microbial processes if the soil will thaw.

About 19% of the Northern permafrost areas is covered by peatlands. Peatland ecosystems often have the highest C content per unit area among different land forms in the mosaic-like permafrost terrain (up to 150-195 kg C m⁻² in 0-3 m; Tarnocai et al. 2009, Hugelius et al. 2011). Particularly high C stocks in the Subarctic can be found in peat plateaus, large flat-topped expanses of permafrost peatlands heaved up by frost (French, 2007). A major part of these peat deposits has been accumulated during warmer climatic conditions in the early and mid Holocene before cooling and onset of permafrost slowed down the rate of peat accumulation (Oksanen et al. 2001, Sannel and Kuhry 2009). On upland tundra underlain by mineral soils the C content is usually lower than in tundra peatlands, but very high C stocks have been found in soils affected by cryoturbation (up to 160 kg C m⁻² in 0-3 m; Bockheim 2007, Tarnocai et al. 2009). Cryoturbation means soil movement and mixing due to frost action (French, 2007). This process buries fresh organic matter to deeper soil layers, where decomposition is limited by low temperatures and lack of oxygen. As a result, cryoturbation usually enhances soil C storage in upland soils (Bockheim 2007, Kaiser et al. 2007).

Plant biomass typically represents only a small part of total C and N pool in high-latitude ecosystems (Bazilevich, 1993, Hugelius et al. 2011). The main factors limiting plant growth in tundra are low temperatures during the growth period, high abundance of wet soils and long snow cover, and resulting low nutrient availability due to slow turn-over of organic matter (Shaver and Chapin 1995, Shaver et al. 2001). The nutrient limitation of tundra ecosystems has been

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1.2 CLIMATE CHANGE IN THE ARCTIC

Many changes are anticipated in the arctic environment with climate change, one very relevant being the threat to the large C and N pools in northern permafrost soils. Enhanced release of C and N from high-latitude ecosystems to the atmosphere could lead to a positive feedback loop further accelerating climate change. Global climate models predict for arctic areas stronger warming than for the globe on average and increased precipitation (Kattsov et al., 2005). By 2100, the annual mean temperatures are predicted to increase by 5-7°C and the precipitation by 5-35 %, the largest changes taking place during autumn and winter. Indications of warming have already been observed: The period 2005-2010 was warmer in the Arctic than any five-year period since the surface air temperature measurements began in the late 19th century (AMAP, 2011). Further, reduced snow cover, higher permafrost temperatures and deeper active layers have been observed across the pan-arctic region during the past decades (AMAP, 2011). These changes are affecting the functioning and composition of high-latitude ecosystems in a very complex way, not yet sufficiently understood.

1.3 GREENHOUSE GAS EXCHANGE IN HIGH-LATITUDE ECOSYSTEMS

From the three most important long-lived GHGs, carbon dioxide (CO₂) is the one that has been most broadly studied is tundra ecosystems. This can be justified, since CO₂ is causing the largest radiative forcing (RF) of the three gases, thus being the strongest contributor to global warming (63% of the RF caused by long-lived GHGs; IPCC, 2007). Due to the much lower atmospheric concentrations, the RF of methane (CH₄) and nitrous oxide (N₂O) is lower than that of CO₂ (18 and 6 % of the RF caused by long-lived GHGs, respectively; IPCC, 2007), although they are stronger GHGs per mass unit. According to the global warming potential (GWP) approach (IPCC, 1990), a unit mass pulse emission of CH₄ causes 25 higher climate forcing than that of CO₂ in 100 years time, the same coefficient for N₂O being 298 (IPCC, 2007). The GWP is dependent on the reference period due to different atmospheric life-times of the GHGs. Due to the shorter lifetime of CH₄ (12 years), its relative importance compared to N₂O (lifetime 114 years) and CO₂ is larger at a shorter time horizon.

The gross fluxes of CO₂ in tundra can be orders of magnitude higher on a mass basis than those of CH₄ and N₂O (Heikkinen et al. 2004, Brumwell et al. 2012). However, the net flux of CO₂ can be close to zero and then the uptake or release of the two other gases becomes important for the total climate forcing. Flux assessments including all three gases have been published from many ecosystem types, e.g., agricultural lands (Soussana et al. 2007), tropical and temperate forests (Butterbach-Bahl et al. 2004, Luo et al. 2012), pristine and managed boreal peatlands
(reviewed by Maljanen et al. 2010), savanna (Hao et al. 1988) and Antarctic soils (Gregorich et al. 2006), but comprehensive reports on full GHG balance of northern tundra have been lacking so far.

### 1.3.1 Carbon dioxide and methane fluxes in terrestrial ecosystems

There is a high variability in C fluxes of high-latitude ecosystems both in time and space, but according to a recent meta-analysis the arctic tundra as a whole acts as a net C sink (110 Tg C yr⁻¹; McGuire et al. 2012). Carbon dioxide is the main component of the atmospheric C exchange of tundra (e.g., Fan et al. 1992, Heikkinen et al. 2004, Corradi et al. 2005). Tundra wetlands often are strong CO₂ sinks (e.g., Heikkinen et al. 2002, 2004), while the CO₂ balance of upland tundra with mineral soil is typically closer to zero, and can switch between a C sink and source from year to year (Heikkinen et al. 2004, Lund et al. 2010).

The net response of tundra CO₂ balance to the climate change is still highly uncertain despite the increasing scientific interest the topic has received during the last decades (McGuire et al. 2009). The possible change in the balance results from the sum of the changes in the two opposite gross fluxes: gross photosynthesis (GP) and ecosystem respiration (ER). Many studies suggest that higher temperatures and associated permafrost thaw will enhance decomposition of SOM, increasing losses of old soil C as CO₂ to the atmosphere (e.g., Dorrepaal et al. 2009, Schuur et al. 2009, Vogel et al. 2009, Natali et al. 2011). However, the increased respiration can be partly or fully compensated by the concurrent increase in CO₂ uptake by plants (Vogel et al. 2009, Qian et al. 2010, Natali et al. 2011, Trucco et al. 2012). So called arctic greening, caused by expansion and better growth of deciduous shrubs, has been observed during the last decades (Sturm et al. 2001, Forbes et al. 2010). Besides the direct positive effect of warmer temperature, growth of fast-growing plant species is stimulated by better nutrient availability related to faster mobilization of nutrients from soil organic matter (Chapin et al. 1995).

The results from multiannual studies from arctic and subarctic ecosystems are partly contradictory to each other with respect to environmental controls of the ecosystem CO₂ sink. Earlier snow-melt and longer growing season led to higher seasonal net uptake of CO₂ in a subarctic fen in Northern Finland (Aurela et al. 2004), but not in a graminoid tundra in Northeastern Siberia (Parmentier et al. 2011). In the later study, warm temperatures during growing season promoted GP but also ER, so that the net effect on ecosystem CO₂ sink was insignificant. In a high-arctic heath in Greenland warmer temperatures initially increased ecosystem C sink but only up to a certain limit, above which ER kept increasing while GP leveled off (Groendahl et al. 2007, Lund et al. 2012). These results show that, similarly to the present C balance of tundra, also its response to climate warming varies a lot between various tundra types, and it is important to account for the whole range of this variability when planning studies on tundra C balance.

Although CH₄ comprises a smaller part of the gross C fluxes in the Arctic and many abundant tundra surfaces have negligible CH₄ fluxes, the tundra biome is a globally important source of CH₄ due to high emissions from tundra wetlands (19 Tg C yr⁻¹; McGuire et al. 2012). Methane is produced in water-saturated layers of wetlands by obligately anaerobic methanogenic archaea (Whalen 2005). Depending
on the position of ground water table and the depth of the aerobic soil layer, up to 90% of the produced CH$_4$ can be oxidized to CO$_2$ by methanotrophic bacteria before entering the atmosphere (Oremland and Culbertson 1992). Permafrost distribution largely determines the CO$_2$ and CH$_4$ fluxes from subarctic peatlands. On frozen palsa and peat plateau surfaces aerobic conditions and ombrotrophy cause low emissions of CH$_4$ and small net flux of CO$_2$, while unfrozen fens with high-water tables show high CH$_4$ efflux and CO$_2$ uptake (Nykänen et al. 2003, Heikkinen et al. 2004). Thus, permafrost thaw resulting in increased coverage of wet peatland surface has strong consequences on regional C exchange (Johansson et al. 2006). Small uptake of CH$_4$ has been observed in tundra and forest tundra soils (Christensen et al. 1997, Sjögersten and Wookey 2002, Flessa et al. 2008).

1.3.2 Carbon dioxide and methane fluxes from lakes and ponds
Arctic lakes and ponds usually show release of CO$_2$ and CH$_4$ to the atmosphere (Kling et al. 1991, Kling et al. 1992, Bastviken et al. 2011), fuelled by C input from surrounding terrestrial ecosystems by leaching and erosion. So-called thermokarst lakes, formed by degradation of permafrost, are known as hot spots of arctic CH$_4$ emissions (Walter et al. 2006, Blodau et al. 2008, Desyatkin et al. 2009, van Huiststenen et al. 2011). The high CH$_4$ emissions from thermokarst lakes can be explained by the quality of C substrates: C released from permafrost C pool at thawing can be fairly undecomposed and, therefore, labile (Zimov et al. 1997, Walter et al. 2006). Trace gas emissions from lakes can take place by diffusion or ebullition that means abrupt gas release from the sediment as bubbles. While ebullition is only a minor pathway of CO$_2$ emissions from water-bodies, it is highly important for CH$_4$, comprising up to 95% of the total CH$_4$ flux from thermokarst lakes (Walter et al. 2006). Some of the reported lake CH$_4$ emissions without the ebullitive CH$_4$ flux component (Kling et al. 1992, Heikkinen et al. 2004) are likely underestimates.

As lakes and ponds represent sources of terrestrially fixed C to the atmosphere in high-latitude landscapes that generally act as C sinks (Bastviken et al. 2011), changes in their abundance are relevant for the regional C balance. Remote sensing studies from different parts of the Arctic tell different stories on the thermokarst lake dynamics during the second half of the 20$^{th}$ century. While increase in the lake area has been observed in some permafrost regions (Riordan et al. 2006), the number and area of water bodies has decreased in others due to improved drainage as a result of permafrost thaw (Smith et al. 2005, Jones et al. 2011). The formation of thaw lakes and ponds is not always indicative for unidirectional changes in the permafrost coverage. As a part of the normal thermokarst dynamics the development of thermokarst lakes and ponds is often followed by re-growth and permafrost aggradation, making the increase in CH$_4$ (and CO$_2$) release only temporary (van Huiststenen et al. 2011).

1.3.3 Nitrous oxide fluxes
The few studies published on N$_2$O exchange in permafrost soils usually report small or negligible emissions (Christensen et al. 1999, Ludwig et al. 2006, Rodionow et al. 2006, Ma et al. 2007, Takakai et al. 2008, Siciliano et al. 2009). Recently, N$_2$O uptake
has been reported in polar desert soils with relatively low soil moisture (Stewart et al. 2012). Aerobic nitrification (oxidation of ammonium (NH₄⁺) to nitrite (NO₂⁻) and nitrate (NO₃⁻)) and anaerobic denitrification (reduction of NO₃⁻ and NO₂⁻ to nitric oxide (NO), N₂O and dinitrogen (N₂) gas) are the two main processes responsible from N₂O production in soils (Richardson et al. 2009). The key reason for the low N₂O emissions from pristine arctic ecosystems in general is shortage of mineral N for microbial processes due to the slow mineralization of organic matter in cold climates (Nadelhoffer et al. 1991) and low N deposition (Dentener, 2006). However, studies on N₂O exchange have been mostly carried out on upland tundra with mineral soil, while tundra peatlands have been ignored. Boreal peatlands often show N₂O uptake in pristine stage, but large emissions are induced by draining them for economic use (Martikainen et al. 1993, Regina et al. 1996, Maljanen et al. 2010). Lowering of the water level enhances mineralization of organic N from peat that previously has been preserved in anaerobic conditions. As a result, availability of mineral N for soil microbial activity, including N₂O production, increases. On this background, permafrost peatlands with their large organic N reservoirs and oxic conditions in the upper peat profile due to uplifting by permafrost appear as potential sources of N₂O. Moreover, peat plateaus have patterned ground features completely lacking vegetation (see Section 1.6), where soil microbes do not have to compete for inorganic N with plants. In this work, N₂O fluxes were investigated from all main land cover types of a subarctic landscape, but a special focus was on peat plateau environment due to the facts discussed above.

1.4 METHODS USED TO MEASURE TRACE GAS EXCHANGE IN TUNDRA

Previous studies show that GHG fluxes in tundra exhibit high seasonal (e.g., Laurila et al. 2001, Wagner et al. 2003), interannual (e.g., Rennermalm et al. 2005, Humphreys and Lafleur 2011) and spatial (e.g., Heikkinen et al. 2004) variability. The measuring techniques used in flux studies in tundra should account for this variability in a satisfactory way. At the same time, researchers face logistical difficulties when working in remote arctic areas, and are often forced to make compromises with respect to selection of the measuring techniques and duration and timing of the field campaigns. Due to the limitations related to power supply, accessibility and harsh conditions during the winter season, most of the published GHG flux studies from arctic and subarctic ecosystems are limited to the summer growing season (McGuire et al. 2012), but the number of reports with year-round flux measurements is increasing (e.g., Aurela et al. 2004, Vogel et al. 2009, Jackowicz-Korczynski et al. 2010).

where eddy covariance and chambers have been used in parallel are far more rare (Soegaard et al. 2000, Zamolodchikov et al. 2003, Fox et al. 2008, Sachs et al. 2010).

In this work, a combination of manual chambers operated by University of Eastern Finland (CO₂, CH₄ and N₂O; Chapters 2, 3, 4 and 5) and eddy covariance operated by University of Copenhagen (CO₂, CH₄; Chapters 2 and 3) was used. Table 1 summarizes the strengths and weaknesses of the two flux measuring techniques. With integrative micrometeorological EC technique it is possible to obtain continuous, integrative flux over a source area of 0.1-1 km² and catch the short-term variations in gas exchange, but extrapolation of EC data over larger regions is dependent on representative site selection that is not always feasible (Kim et al. 2006).

**Table 1 Comparison of the two measuring techniques used to measure GHG fluxes in terrestrial ecosystem in this study.**

<table>
<thead>
<tr>
<th>Measuring technique</th>
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<tbody>
<tr>
<td>Eddy covariance</td>
<td>+ good temporal resolution</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ better areal coverage than that of chamber technique</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ minimal disturbance of the ecosystem studied</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- limited information on spatial variability in the fluxes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- limitations in operating conditions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- difficulties to extrapolate the fluxes to a larger area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- high cost</td>
<td></td>
</tr>
<tr>
<td>Manual chamber technique</td>
<td>+ good spatial resolution</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ inexpensive, independent of mains power</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ possibility to relate fluxes to the environmental conditions at microsite level</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ allows extrapolation of the fluxes to larger areas</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- high demand for manpower</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- low temporal resolution</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- low areal coverage if spatial extrapolation is not done</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- disturbance caused to the studied system</td>
<td></td>
</tr>
</tbody>
</table>

On the other hand, chamber measurements give information on spatial variability in fluxes of different functional ecosystem types and their dependence on local environmental conditions. This kind of data are particularly useful when the aim is to upscale the flux data to regional estimates in highly fragmented environments like tundra (Heikkinen et al. 2004, Flessa et al. 2008, Fox et al. 2008). Automated chambers represent an intermediate variant between the EC and manual chamber techniques with respect to temporal and spatial resolution and cost. The decision between manual and automated chambers was made in favor of the manual ones based on independence of mains power, lower cost and possibility to include a large number of microsites (10) in order to cover all the dominant land cover types in the studied landscape.

During the snow cover fluxes were determined using the snow gradient technique, where flux is calculated from the concentration gradient between the snow-pack and the atmosphere using gas-specific diffusion coefficients
General introduction

(Sommerfeld et al. 1993; Chapters 2, 3, 4 and 5). Maljanen et al. (2003) showed on boreal organic soils that this measuring technique and chamber method give rather similar flux rates. The winter measurements were few in number but caught different periods of winter season: autumn freezing in October, mid-winter in January and March and spring thaw in May-June.

In addition to the terrestrial ecosystems, gas exchange was measured from thermokarst lakes (Chapters 2 and 3). The different emission pathways, diffusion and ebullition, were accounted for by using a combination of two measuring techniques. Diffusive emissions were determined with a thin boundary layer (TBL) method, where flux is calculated from gas concentration in the surface water and local wind speed (Liss and Slater 1974). Permanently installed submerged gas collectors, similar to those used by Huttunen et al. (2001), were used for measuring the ebullitive flux. The combination of these two methods was proved suitable for measuring CO₂ and CH₄ dynamics in small peatland lakes in Western Siberia (Repo et al. 2007).

1.5 AREAL INTEGRATION OF GREENHOUSE GAS FLUXES

For correct estimation of regional GHG balances it is as important to extrapolate the collected data correctly as it is to perform accurate measurements. This requires representative selection of study sites, but also information on the spatial extent of various land cover types. The term land cover type is used in this work to refer to an ensemble of vegetation and underlying soil.

For a heterogeneous environment like tundra correct spatial upscaling of the fluxes is a demanding task. In earlier studies, regional flux estimates of tundra have been based on i) modeling approaches using remote sensed or measured explanatory variables (e.g., normalized difference vegetation index (NDVI), soil moisture, temperature, thaw depth) and measured flux data (Oechel et al. 2000, Stoy et al. 2009, Lee et al. 2012) or ii) land cover classification and weighing the fluxes of different landscape units by their coverage (Heikkinen et al. 2004, Flessa et al. 2008, Fox et al. 2008, Sachs et al. 2010). The spatial data for previous upscaling exercises have been obtained from either Landsat satellite images (resolution 30 m, scene size ~30 000 km²; Soegaard et al. 2000, Heikkinen et al. 2004), QuickBird satellite images (resolution 0.6-2.4 m, scene size 100 km²; Flessa et al. 2008), aerial photography (resolution 0.5 m; Sachs et al. 2010) or ground observations in a regular grid (resolution 5 m; Fox et al. 2008, Lee et al. 2011). In practice, there is often a trade-off between the areal extent and the spatial resolution. Landsat images are suitable for broad vegetation mapping, but they are not detailed enough to detect the small scale variability typical for tundra (Laidler and Treitz 2003). The high-resolution QuickBird satellite images used in this study provide a rather optimal combination of a scene size of a regional scale and a resolution high enough to realistically represent the tundra landscape.

While the above-mentioned extrapolation studies have operated in two scales (plot-to-landscape or plot-to-regional), the nested study design of the present work included three scales: flux measurements in two sequential scales and extrapolation...
to the regional scale using high-resolution QuickBird satellite data. The landscape level was used as an intermediate step that allowed verification of the plot scale CO2 and CH4 fluxes obtained by chamber and gas gradient techniques against EC fluxes for before extrapolating them to the regional level (Chapters 2 and 3).

1.6 STUDY SITES

The most of the data for this thesis were collected at a southern tundra site located near the settlement of Seida in the Komi Republic, Northeast European Russia (67°03’N, 62°57’E, 100 m a.s.l.; Fig. 1). The Seida site was selected as one of the two intensive flux sites of a EU-funded research project that aimed at quantifying the C budget in Northern Russia in past, present and future (CARBO-North; see http://www.carbonnorth.net/). The mean annual air temperature in the study region is -5.6 °C and the mean annual precipitation is 501 mm (long-term averages for 1977-2006, data from Vorkuta station (67°48’N, 64°01’E, 172 m a.s.l.); Komi Republican Center for Hydrometeorological and Environmental Monitoring). The study site is located close to the northern tree line, and has isolated forest patches with spruce and fell birch as dominant tree species. It is underlain by discontinuous permafrost (permafrost coverage of 50-90%). The location on the southern edge of the permafrost zone and proximity to the forest border make this site interesting from the climate change point of view: Rapid changes can be expected with respect to vegetation cover and permafrost distribution. The region is already experiencing permafrost warming and thaw, as reported by Oberman (2008).

![Figure 1 Location of study sites: The main study site Seida in Komi Republic, Russia (67°03’N, 62°57’E) and palsa mires Luovdijeäggi (69°35’N, 26°11’E), Tsullovejeäggi (69°35’N, 26°12’E) and Vaisjeäggi (69°49’N, 27°10’E) in Utsjoki, Finnish Lapland. The dashed line indicates the Arctic Circle.](image-url)
A distinctive characteristic of the study site are peat plateaus, massive permafrost peatlands with up to several meters thick frozen peat deposits (Fig. 2b). They have by far the largest belowground C stocks per unit area in the whole landscape. According to a soil C inventory done at the Seida site, the below ground C stock for the upper 3 m in peat plateaus is 150.8 g C m$^{-2}$, while the mean for the whole study site is 40.5 g C m$^{-2}$ (Hugielus et al. 2011). In the peat plateaus the peatland surface is heaved up by frost and, as a result, the peat layer above the permafrost table is mostly well drained and overlain by ombrotrophic bog vegetation. The depth of the seasonal thaw, or active layer depth, is shallow in the peat plateaus due to low thermal conductivity of unfrozen, dry peat. Compared to another type of permafrost peatlands, palsa mires existing in milder climate in the sporadic permafrost zone, peat plateaus have more frozen surfaces relative to unfrozen ones (see Chapter 5).

Peat plateaus contain unvegetated peat surfaces, so called peat circles (Fig. 2d). Peat circles are round patches of bare peat partly covered by a thin moss layer but without any vascular plants. The irregular and bumpy peat surface and high ice content during the winter suggest that these surfaces are affected by cryoturbation, soil mixing by frost action (Bockheim and Tarnocai 1998). Wind abrasion of the surface peat leads to formation of bare peat surfaces on palsa mires, and it might be also the initial factor behind the peat circle formation on peat plateaus. Small and
shallow thermokarst lakes, initialized by local thawing of permafrost, are also mostly located within the peat plateau.

Peat plateaus and thermokarst lakes are surrounded by narrow stripes of unfrozen waterlogged fens that act as water conduits in the terrain (Fig. 2c). Fens are typically mesotrophic and have a floating *Sphagnum* mat. Willow stands growing on the low lying parts of the landscape are also typical for the region. They have the highest C stocks in above ground plant biomass of all land cover types except for the small forest stands (Hugelius et al. 2011). Most of the landscape in the region is hilly upland with tundra heath vegetation and thin organic layer underlain by mineral soil (Fig. 2a). These areas have shrub tundra vegetation dominated by *Betula nana*, *Salix* sp., dwarf shrub, mosses and lichens.

The CO$_2$ and CH$_4$ dynamics have been studied earlier with the manual technique in the same region, around 40 km north from the Seida site by Heikkinen et al. (2002, 2004). In addition, Zamolodchikov et al. (2000) measured summer time CO$_2$ dynamics of different tundra plant communities with manual chambers at two sites located further north from Seida. Nevertheless, Northeast European Russian tundra is underrepresented concerning GHG flux studies and it is lacking a permanent research facility that would provide long term data on trace gas flux dynamics.

*Figure 3* Bare palsa surfaces on Luovdijeäggi palsa mire in Northern Finland. Photograph by Maija Marushchak.

In addition to the Seida site, N$_2$O fluxes were measured from three palsa mires, Luovdijeäggi (69°35’N, 26°11’E, 370 m a.s.l.), Tsulloveijeäggi (69°35’N, 26°12’E, 365 m a.s.l.) and Vaisjeäggi (69°49’N, 27°10’E, 295 m a.s.l.), located in the sporadic permafrost zone in Utsjoki, Northern Finland (Fig. 1). This region has a milder climate than the Seida site, with a mean annual air temperature of ~1.7 °C and mean annual precipitation of 414 mm (long-term averages for 1962-2006, data from Utsjoki-Kevo station (69°45’N, 27°00’E, 107 m a.s.l.); Finnish Meteorological Institute). Typical palsas on the studied mires are 1 to 3 m high with a diameter of
20 to 50 m (Fig. 3). Vegetation on palsa is small-statured and consists of dwarf shrubs, especially Emptetrum hermaphroditum, herbs (e.g., Rubus chamaemorus), mosses (Dicranum spp., Pleuverium spp.) and lichens. A large part of the palsa surface is unvegetated due to wind abrasion that has removed up to several tens of centimetres of peat (Seppälä 2003). Frost boils, small patches of bare soil formed by cryoturbation frequently occur on mineral soils around the palsa mires.

1.7 AIMS OF THE STUDY

The aim of this thesis was to determine the regional GHG balance of a heterogeneous southern tundra landscape. For the first time, N₂O was included in such a regional flux assessment in tundra in addition to CO₂ and CH₄. The specific goals of the study were:

- To understand the spatial variability in the fluxes of CO₂, CH₄ and N₂O, and the factors behind this variability by plot scale measurements based on chamber and gas gradient techniques.
- To verify the accuracy of upscaling of the plot scale fluxes in the landscape scale against integrative eddy covariance measurements.
- To estimate the regional GHG balances by integrating the plot scale fluxes over the study region using high resolution satellite data.
- To assess the relative importance of CO₂, CH₄ and N₂O to the total climate forcing of different land cover types and of the subarctic tundra region, with implications for climate change.
2  Carbon dioxide balance of subarctic tundra from plot to regional scales

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3 Methane dynamics in warming tundra of Northeast European Russia

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4 Large $\text{N}_2\text{O}$ emissions from cryoturbated peat soil in tundra

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5  Hot spots for nitrous oxide emissions found in different types of permafrost peatlands

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6 Regional greenhouse gas balance and net radiative impact of subarctic tundra

6.1 INTRODUCTION

Subarctic tundra is a mosaic of various land cover types - ensembles of vegetation and underlying soil - that alternate within distances from tens to hundreds of meters. This is a result of variation in topography, hydrology and permafrost distribution, factors that are interrelated in complex ways. Different land cover types show strong differences concerning fluxes of the three important greenhouse gases (GHGs), CO₂, CH₄ and N₂O (Chapters 2, 3, 4 and 5). While there are numerous studies on the full atmospheric C balance (CO₂ + CH₄) of tundra landscape (e.g., Heikkinen et al. 2002, 2004, Wille et al. 2008, Bäckstrand et al. 2010), there are, to our knowledge, no studies that have included also N₂O in the total GHG balance estimated over an extended period. This can be explained by the assumption that N₂O fluxes are unimportant in pristine high-latitude ecosystems, a concept questioned by recent results showing that some subarctic and arctic soils have potential for high N₂O emissions (Chapters 4 and 5 of this thesis; Elberling et al. 2010). Also N₂O sink capacity has been observed lately in high Arctic soils (Stewart et al. 2012). Furthermore, while many of the earlier studies on tundra greenhouse gas balance have been focused only on certain (dominant) land cover types, in this study the GHG fluxes were determined from all important elements of a heterogeneous subarctic tundra landscape ranging from terrestrial to aquatic, mineral to peat soils, water-logged to dry and from complete lack of vegetation to dense cover of tall shrubs.

This chapter brings together the results of different sub-studies on CO₂, CH₄ and N₂O (Chapters 2 to 5) in order to achieve the ultimate goal of this thesis: estimating the total annual GHG balance and the net radiative impact of the study region of 98.6 km² located in Northeast European Russia in the discontinuous permafrost zone. In order to compare the importance of different GHGs and land cover types, the emissions of different gases were converted to CO₂ equivalents using the GWP approach (IPCC, 1990; Chapter 1.3).

6.2 METHODS

The flux data used to calculate the total regional CO₂ and CH₄ balances are reported in Chapters 2 and 3, respectively. These chapters describe in detail the methods used: chambers and snow gradient methods for terrestrial ecosystems and thin
boundary layer method and bubble gas collectors for lakes. For the regional N₂O flux estimate, the more extensive data set reported in Chapter 5 was used instead of the one snow-free period data reported in Chapter 4. As for CO₂ and CH₄, the growing season N₂O flux is from 2008 (16 June to 2 September; 79 days) and the annual estimate is reported for the period from 6 October 2007 to 5 October 2008. The numbers are somewhat deviating from those reported in Chapter 5, where the growing season flux is the average from 2007 and 2008, and annual flux is the sum of this mean growing season flux and the cold season flux 2007-2008.

A common procedure was needed for extrapolating the plot scale fluxes of different gases to the regional scale. In Chapter 2 the regional CO₂ balance was estimated by two independent upscaling methods: i) by weighing the unit-area fluxes of different land cover types with their percent coverage according to a land cover classification (the LCC approach) and ii) by using the linear dependence between LAI and CO₂ fluxes, observed in the plot scale, and the mean growing season leaf area index (LAI) for the study region obtained by remote sensing (LAI map approach). These two approaches gave rather similar results (see Chapter 2). For calculation of the regional net radiative balance only the results of the LCC approach are used, since it was the method used for upscaling the CH₄ fluxes and directly applicable also for extrapolating N₂O fluxes. When the high N₂O emissions from peat circles were scaled up in Chapter 4, the small N₂O fluxes per unit area from all the other surfaces were set to zero. Here, the actual measured N₂O flux values were used for each land cover type.

The uncertainties for regional estimates were calculated as described in Section 2.7: the standard deviations (SDs) of hourly/daily microsite fluxes were weighed with corresponding area contributions and these area-weighed SDs were summed up over time. Finally, CH₄ and N₂O fluxes were transformed into CO₂-equivalents with the GWP approach (IPCC, 2007) to allow calculation of net radiative balance including all three gases. This approach takes into the account the radiative forcing per mass unit and life-time of different gases. From the three time horizons commonly used in GWP assessments - 20, 100 and 500 years - the intermediate reference period of 100 years was selected here. A shorter time interval would have overemphasized the meaning of CH₄, while a very long time horizon would have been irrelevant considering the time scale of the anticipated climate changes in the subarctic. Thus, the coefficients used to convert mass emissions of CH₄ and N₂O to CO₂ equivalents were 25 and 298, respectively (IPCC, 2007).

6.3 THE REGIONAL CLIMATE FORCING AND THE IMPORTANCE OF DIFFERENT GREEN HOUSE GASES

The regional balance estimates and climate forcing of different GHGs as CO₂ equivalents are summarized in Table 1. On an annual basis the study area acted as a small (and insignificant) sink of CO₂ of -41 ± 57 g C m⁻² and a small source of CH₄ (5.0 ± 1.3 g C m⁻²) and N₂O (5.8 ± 7.1 mg N m⁻²). The annual C balance (CO₂ + CH₄) was -36 ± 54 g C m⁻². When considering all the three gases the total climate forcing of the study region in the study year was close to zero (20 ± 214 g CO₂-eq m⁻² yr⁻¹; Table
1), meaning that the effect of the region on the climate was almost neutral. Considering the high interannual variability in the subarctic and arctic GHG fluxes in other studies (e.g., Rennermalm et al. 2005, Humphreys and Lafleur 2011), it is likely that the study region switches between a net sink and source of GHGs from year to year. However, during the growing season from mid June to early September the region was a net sink of GHGs with significantly negative radiative impact of -226 ± 131 g CO₂-eq m². Although the measurements carried out during the cold season did not show very high emission peaks, a phenomenon often observed in northern soils (e.g., CO₂: Bubier et al. 2002; CH₄: Mástepanov et al. 2008; N₂O: Maljanne et al. 2009), the large difference between growing season and annual GHG balance indicates high importance of winter. All three GHGs showed emissions during the winter, and when accumulating over the long winter time even small daily fluxes become important (see also Aurela et al. 2002).

Methane has a rather minor role in the total C balance of the studied subarctic landscape: 4% of the net C sink as CO₂ was lost as CH₄-C during the growing season and the annual CH₄-C loss was 12% of the net CO₂-C sink. However, when calculated as CO₂-equivalents the CH₄ emissions reduced the growing season GHG sink by 34%, and overruled the CO₂ sink on an annual basis. The important role of CH₄ for the total radiative impact of northern peatlands is well-known from previous studies (e.g., Friborg et al. 2003, Frolking et al. 2006, Johansson et al. 2006). The results here stress that even if over 80% of the terrain has negligible CH₄ fluxes, CH₄ can still have a great importance for regional climate forcing. The regional N₂O emission was very low, and its importance for the regional radiative impact was marginal.

Table 1 Regional greenhouse gas (GHG) balance of the study region of 98.6 km². The total GHG balance as CO₂-equivalents, i.e., the net radiative impact was calculated using the GWP approach with a 100-year time horizon (coefficients for CH₄ = 25 and N₂O = 298). Negative values indicate GHG a sink/cooling effect; positive values indicate a GHG source/warming effect.

<table>
<thead>
<tr>
<th></th>
<th>Growing season balance</th>
<th>Annual balance</th>
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<tbody>
<tr>
<td><strong>CO₂</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g C m⁻²</td>
<td>-94 ± 37</td>
<td>-41 ± 57</td>
</tr>
<tr>
<td>g CO₂ m⁻²</td>
<td>-344 ± 136</td>
<td>-150 ± 208</td>
</tr>
<tr>
<td><strong>CH₄</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g C m⁻²</td>
<td>3.5 ± 0.8</td>
<td>5.0 ± 1.3</td>
</tr>
<tr>
<td>g CO₂-eq m⁻²</td>
<td>118 ± 26</td>
<td>168 ± 45</td>
</tr>
<tr>
<td><strong>N₂O</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mg N m⁻²</td>
<td>1.4 ± 3.1</td>
<td>5.8 ± 7.1</td>
</tr>
<tr>
<td>g CO₂-eq m⁻²</td>
<td>0.6 ± 1.4</td>
<td>2.7 ± 3.3</td>
</tr>
<tr>
<td><strong>TOTAL C BALANCE</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(CO₂ + CH₄) g C m⁻²</td>
<td>-91 ± 34</td>
<td>-36 ± 54</td>
</tr>
<tr>
<td><strong>TOTAL GHG BALANCE</strong> (CO₂ + CH₄ + N₂O)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>g CO₂-eq m⁻²</td>
<td>-226 ± 131</td>
<td>20 ± 214</td>
</tr>
</tbody>
</table>
Figure 1 Radiative impact of different land cover types as CO₂-equivalents over a 100-year time horizon (n = 3-6). Top: Fluxes of CO₂, CH₄ and N₂O; middle: Total GHG balance including the three GHGs, bottom: GHG balance weighed by area coverage of each land cover type (%), indicated on the x-axis. This representation illustrates the relative importance of different land cover types for regional flux. Negative flux values indicate a GHG sink/cooling effect; positive values indicate a GHG source/warming effect.
6.4 CLIMATE FORCING OF DIFFERENT LAND COVER TYPES AND THEIR IMPORTANCE FOR THE REGIONAL BALANCE

From the eight land cover types studied only shrub tundra heath, *Betula nana* tundra heath and tundra bog were (insignificant) GHG sinks as CO₂-equivalents on an annual basis (Fig. 1). They were characterized by small net CO₂ uptake rates and very low fluxes of CH₄ and N₂O. However, these three land cover types have high area coverage in the studied terrain, so they were important for the regional climate forcing (Fig. 1). The other five land cover types had a net warming impact on climate, also the wetlands that showed strong C sink but had large CH₄ emissions. The willow stands, covering 8% of the study region, were important to the regional C balance and CH₄ emission due to their high C gas fluxes on a unit area basis (Chapters 2 and 3).

The two extreme land cover types concerning the total climate forcing caused by GHG fluxes exist at small distances on the peat plateau peatlands. From all land cover types studied the unvegetated peat circles had the highest positive radiative impact per unit area, 724 ± 282 g CO₂-eq m⁻² y⁻¹, due to the high N₂O emissions and large net CO₂ release. There, the N₂O fluxes were responsible for 55% of the annual GHG balance as CO₂ equivalents. In contrast, the vegetated part of the peat plateau, tundra bog, represented the strongest net GHG sink on a unit area basis, -153 ± 174 g CO₂-eq m⁻² y⁻¹. Thus, possible changes in the coverage of peat circles, affected by climate driven cryogenic processes (Chapters 4 and 5), would have implications on the total climate forcing of the peat plateaus. The same applies to the relative coverage of peat plateaus with shallow seasonal thaw depth vs. fens with deeper active layer, which is determined by permafrost distribution and, thus, climatic changes. In northern Scandinavia, the increased abundance of wetlands as a result of permafrost thaw has been already observed (Christensen et al. 2004, Johansson et al. 2006). Due to the net cooling effect of frozen peatlands and the net warming effect of unfrozen ones, the decreased permafrost coverage of high-latitude peatlands would act as a positive feedback to the climate warming.
7 General discussion

7.1 REGIONAL GREEN HOUSE GAS BALANCES

A recent extensive review of arctic C flux studies by McGuire et al. (2012) provides a good reference for the CO₂ and CH₄ balances of this study. In general, the review shows stronger CO₂ sink for the Northern European Arctic compared with other arctic regions, which could be explained by relatively mild climatic conditions, as discussed in Chapter 2. The growing season estimate for the CO₂ balance of the Seida study site, -127 ± 30 to -94 ± 37 g C m⁻² (Chapter 2), is similar to the average of -94 g C m⁻² for Northern Europe (McGuire et al. 2012), but on an annual basis Seida was a stronger sink than the North European mean (-79 ± 22 to -41 ± 57 g C m⁻² vs. -30 g C m⁻²). Furthermore, high summer temperatures in Seida during the study years 2007-2008 may have increased the gross CO₂ fluxes, the effect on net C balance being less clear (Parmentier et al. 2011, Lund et al. 2012).

High temperatures during peak summer likely enhanced also CH₄ release from the study region (Zhuang et al. 2004). In 2007, an increase of 8.3 ± 0.6 ppb was observed in globally averaged atmospheric CH₄ concentration. This increase could be partly attributed to anomalously high temperatures in the Arctic that lead to high emissions from arctic wetlands (Dlugokencky et al. 2009). The high temperatures directly promoted CH₄ emissions from Seida wetland sites, since they did not experience summer drought due to the floating fen surface that adjusted to the fluctuations of water level (Chapter 3). The regional CH₄ emissions were 3.5 and 5.0 g C m⁻² for the growing season and whole year, respectively (Chapter 3), which is lower than the averages for Northern Europe (McGuire et al. 2012). A reason for this could be lower wetland coverage in Seida compared to the reference studies. Wetlands are higher CO₂ sinks and CH₄ sources than uplands (McGuire et al. 2012), and the C balance is strongly affected by the percent coverage of wet ecosystem types. In general, data from separate sites has regional meaning only if it can be put to the spatial context based on knowledge on distribution of different tundra types.

According to the only previous study on regional C balance of tundra in Northeast European Russia (Heikkinen et al. 2002, 2004), the landscape was a net C source of 35 g m⁻² during summer season from June to September 2001. The C balance of different land cover types varied from a sink of -110 g C m⁻² to a source of 123 g C m⁻². In contrast, the results of this study show significant C sink during the growing season of 91 ± 38 g C m⁻², ranging from -264 to 48 g C m⁻² across the land cover types. The distribution of different land cover types in the study by Heikkinen et al. (2004) was rather similar to that of our study. However, fluxes were not measured from willow dominated stands, covering 24% of the terrain, and they were assumed to have a neutral C balance. According to the results of the present work, the willow stands actually show a very strong C sink character (Fig. 1). If the C balance of willows measured in Seida, -265 g C m⁻² for 6 June-10 September (-295 g CO₂-C m⁻² + 30 g CH₄-C m⁻²), is used to recalculate the regional balance by
Heikkinen et al. (2004), it switches from a C source of 35 g m\(^{-2}\) to a C sink of -30 g m\(^{-2}\). The contribution of willow stands on the regional CH\(_4\) balance is even higher. Measuring CH\(_4\) fluxes from willow stands would have likely increased the regional CH\(_4\) emission from 1 g C m\(^{-2}\) (range -0.2-14 g C m\(^{-2}\)) estimated by Heikkinen et al. (2004). To conclude, willow stands are highly important for tundra C balance in Northeast European Russia.

The regional N\(_2\)O estimate of this study, 5.8 ± 7.1 mg N m\(^{-2}\) yr\(^{-1}\) (Chapter 6), is the first one published for tundra. The value is low due to the low coverage of the high emitting sites, peat circles, despite the large emissions on a square meter basis (growing season mean 8.1-10.3 mg N\(_2\)O m\(^{-2}\) d\(^{-1}\); Chapter 5). According to the present understanding from Northern Finland (Chapter 5), European Russia (Chapters 4 and 5) and Siberia (Biasi et al., unpublished results), high N\(_2\)O emissions can be found from different parts of the Arctic and Subarctic but they seem to be limited to unvegetated surfaces on palsa mires and peat plateau peatlands.

### 7.2 Spatial Variability in Greenhouse Gas Exchange

#### 7.2.1 Importance of different land cover types for regional carbon dioxide, methane and nitrous oxide balances

Shrub tundra heath, willows and tundra bog were the three land cover types dominating the growing season CO\(_2\) balance: together they were responsible for almost 77% of the growing season net CO\(_2\) sink. Shrub tundra heath and tundra bog cover a large part of the studied terrain, while willow stands are important due to their high C sink capacity per unit area (Fig. 1). The land cover types showing net C source on an annual basis - unvegetated peat circles, dry lichen tundra heath and lakes - had only minor importance to the regional CO\(_2\) balance due to their limited distribution (Fig. 1).

The CO\(_2\) fluxes were rather normally distributed across the land cover types (Chapter 2; Fig. 1). In contrast, clear hot spots or hot areas of CH\(_4\) and N\(_2\)O emissions were found, while the fluxes of these gases were very small from the rest of the landscape (Fig. 1). Willow wetlands, fens and thermokarst lakes, together covering 16% of the study region, were significant CH\(_4\) sources (Fig. 1; Chapter 3). The terrestrial CH\(_4\) sources were responsible for 99% of the regional emission on annual basis, and the contribution of willows alone was as high as 77%, nine times their percent coverage in the landscape. The role of the CH\(_4\) emissions from lakes in the regional scale was only marginal due to their limited distribution (~1%) and rather low emissions on a unit area basis, 3.1 g C m\(^{-2}\) yr\(^{-1}\). It might be that we missed high emissions during the short periods of ice melt and turn-over in autumn and spring (Huttunen et al. 2004, Kankaala et al. 2006). However, we are quite sure based on our field observations that huge winter-time hot spots during the ice-cover, such as described by Walter et al. (2006), did not exist in our study lakes. None of the land cover types studied showed CH\(_4\) uptake on an annual basis.
General discussion

Figure 1 Annual fluxes of CO₂ (ER top left, GP bottom left), CH₄ (top right) and N₂O (bottom right) of different land cover types (bars; n = 3-6) on a unit area basis vs. their percent coverage in the study area of 98.6 km² (crosses). Negative values indicate a GHG sink to the ecosystem, positive values indicate a GHG source to the atmosphere.

Bare peat surfaces on peat plateaus, covering only 0.27% of the study region, were strong N₂O sources with summertime flux rates comparable to those commonly measured from tropical or agricultural soils (Fig. 1; Chapter 4 and 5). The unit area fluxes from the other land cover types were two to three orders of magnitude smaller than those from peat circles (Chapters 4 and 5). However, the contribution of N₂O emissions from tundra bog (0.01 ± 0.01 g N₂O-N m⁻² yr⁻¹) to the regional N₂O balance is as high as 54% due to the high relative coverage in the landscape compared to peat circles (23 vs. 0.27%). Small N₂O uptake was regularly observed at fen surfaces, but the rates were so small that this N₂O sink was unimportant at the regional scale.
7.2.2 Factors explaining the spatial variability in carbon dioxide and methane fluxes

While gross photosynthesis showed ten-fold differences between the terrestrial land cover types, the variability of ecosystem respiration was only three-fold (Fig. 1). A further evidence of the role of recently fixed C as a driver of the spatial variability in the CO\textsubscript{2} balance is that vascular leaf area index (LAI) explained well the variability in NEE, GP and ER across all soil and vegetation types (Chapter 2). Linear correlations between LAI and CO\textsubscript{2} fluxes have been found also in previous studies on tundra and peatlands (Shaver et al. 2007, Street et al. 2007, Lund et al. 2010).

Also CH\textsubscript{4} emission at the nine wetlands plots (willow and fen) had a strong positive correlation with LAI (Chapter 3; see also Morrissey and Livingston 1992). This can be seen as an indication of a tight link between net primary production and methanogenesis and the importance of plant-mediated CH\textsubscript{4} flux through plant aerenchyma (King et al. 1998, Öquist and Svensson 2002, Kutzbach et al. 2004, Ström et al. 2012). Since the studied wetlands had constantly high water table and only a thin oxidative peat layer, the CH\textsubscript{4} emissions were not strongly affected by CH\textsubscript{4} oxidation in soil. Continuously high water level and large differences in vascular plant biomass explain why water table level was unimportant in explaining the spatio-temporal variability in the wetlands studied, in contrast to many earlier reports on CH\textsubscript{4} fluxes in peatlands (e.g., Morrissey and Livingston 1992, Dise 1993, van Huisteden et al. 2005, Turetsky et al. 2008). The seasonal variability in CH\textsubscript{4} emissions was strongly driven by temperature in the anaerobic peat profile (Chapter 3). Increased evapo-transpiration expected with the warmer temperatures will probably not cause significant drying of fens in the Seida region. They are typically floating fens where the peatland surface adjusts to fluctuations of water level, and increased temperatures would likely mean increased CH\textsubscript{4} emissions on a unit area basis.

Due to the high explanatory power of vascular LAI for CO\textsubscript{2} fluxes, we were able to utilize it for the regional extrapolation of the fluxes. In Chapter 2, a regression function between LAI measured in the field and spectral information of a high resolution satellite image was used to produce a LAI map for the study region. The regional LAI derived from the map and the linear regression between LAI and CO\textsubscript{2} balance was used for calculating the regional CO\textsubscript{2} balance. The LAI-CH\textsubscript{4} flux dependence provided a way to explain the higher areal CH\textsubscript{4} flux measured by chambers than by the EC technique: the fen flux plots had higher LAI than the fen in the region on average (Chapter 3). These examples show the value of the fast, simple and non-destructive LAI measurements, and strongly suggest that LAI monitoring should be included in any CO\textsubscript{2} and CH\textsubscript{4} measurement campaign. Many previous C balance studies on tundra ecosystems do not report any estimate for vascular plant leaf area or biomass, and it can be argued that these plant variables may explain a large part of the unexplained variability between the sites. Further, LAI monitoring will be of high interest in long term studies dealing with changes in arctic ecosystems along with the climate change. Multiannual studies would reveal how much do the observed LAI-CO\textsubscript{2} and LAI-CH\textsubscript{4} dependences vary from year to year according to, e.g., climatic conditions.
7.2.3 Large nitrous oxide emissions from bare peat surfaces

Large N₂O emissions found from peat circles at the Seida study site and eroded palsa surfaces on Finnish palsa mires (Chapters 4 and 5) raise N₂O to the agenda of tundra GHG flux research. High emissions of this gas from tundra may be surprising on the background of earlier knowledge on the arctic N cycle (Section 1.3.3). However, they can be well explained by a favorable combination of biotic and abiotic factors occurring at these patches of bare peat. These factors include: i) aerobic conditions created by uplifting of the peat by permafrost, which enables sufficient mineralization of organic matter and nitrification; ii) large stocks of peat with low C:N ratio fuelling the supply of inorganic N and NOₓ; iii) lack of vegetation that leaves the whole inorganic N pool for the soil microbes; and iv) intermediate moisture conditions allowing coupled nitrification-denitrification. Nitrate from nitrification is used as an electron acceptor in denitrification, which likely is the main pathway of N₂O production in the peat circles (Chapters 4 and 5; Palmer et al. 2012). The association between low C:N ratio and high N₂O release has been earlier shown in boreal organic soils (Klemetsson et al. 2005). The present data from palsa mires in Finnish Lapland provide evidence that neither low C:N ratio nor lack of vegetation alone is enough to support high N₂O release - both these factors are required (Chapter 5).

Processes related to the harsh climatic conditions - frost heave, cryoturbation and wintertime wind erosion - are very important for N₂O emissions from permafrost peatlands: They create aerobic conditions in the upper peat profile, remove the vegetation cover and expose the peat with low C:N ratio to the surface (Chapter 4 and 5). Interestingly, the conditions at peat circles and eroded palsa surfaces are similar to those observed in peatlands artificially drained for economic use, known for their high N₂O emissions and high positive radiative forcing as CO₂ equivalents (Martikainen et al. 1993, Maljanen et al. 2010).

Respiration rates were high at peat circles considering lack of plants and the high age of the surface peat (3540 years; Biasi et al. 2013) and also the gross N mineralization rate was rather high (Chapter 5). Similar peat as currently found on the surface at peat circles and eroded palsas exists also in the deeper layers of permafrost peatlands. The rather high decomposability of peat plateau peat means that permafrost thawing and especially thermokarst erosion could rapidly make these deeper peat layers available for decomposition processes (see also Hugelius et al. 2012). This could lead to enhanced N and C cycling and emissions of N₂O (and CO₂/CH₄), providing that water status is favorable. Recent laboratory studies with arctic wetland soils have shown the potential of some permafrost soils for high N₂O release after permafrost thaw, drying and rewetting (Elberling et al. 2010).

The clear temperature response of N₂O emissions from peat circles (Chapter 5) would mean higher emissions in future warmer climate. Moreover, the small N₂O release occasionally observed at vegetated peat plateau surfaces in this work imply that the peat plateau as a whole has potential for N₂O release, and larger emissions might be induced by climate change. Although N₂O emissions currently have only marginal importance for the regional climate forcing, the phenomenon as such complements the understanding of N cycling in pristine northern ecosystems. There is a need for further studies investigating the mechanisms behind the N₂O emissions...
and the microbial groups responsible for N transformations in the highly acidic peat.

7.3 METHODOLOGICAL CONSIDERATIONS

7.3.1 Spatial extrapolation of greenhouse gas fluxes
Due to the high overall variability in GHG fluxes across subarctic landscape and presence of hot spots, the use of high-resolution satellite data are crucial for meaningful regional extrapolation. Importance of hot spots for the total emissions of CH₄ in pristine ecosystems has been recognized also in previous studies (e.g., Bubier et al. 2005, Flessa et al. 2008). By using high resolution satellite data from a QuickBird image it was possible to catch very accurately the landscape features occurring as small patches, such as peat circles and fens, which are too small to be detected by, e.g., Landsat imagery. However, the results of this work show that in addition to the high fluxes occurring over small areas (such as CH₄ fluxes from willow) also small fluxes occurring over large areas (such as CO₂ fluxes from shrub tundra heath and Betula nana tundra heath and N₂O fluxes from tundra bog) matter when estimating the regional GHG balance and the net climate forcing of subarctic tundra. Accordingly, it is neither justified to limit such studies to a few land cover types that are dominant on area basis nor to concentrate on determination of accurate flux rates of the high-emitting sites only. Both are crucial for regional GHG flux assessments in tundra ecosystems and cannot be prioritized over each other.

Representative selection of measuring locations is also needed for realistic spatial extrapolation. Ecosystem types from peatlands to mineral soil and from aquatic to terrestrial sites studied at the plot scale in the present work represent 97% of the whole study region (Chapter 2). The mean growing season LAI values of the terrestrial microsites varied from 0 to 2, which covers well the variability in vascular LAI in the landscape missing only the extreme high range. According to the LAI map based on a QuickBird satellite image (resolution 2.4 m; Chapter 2), only 0.7% of the study area had a mean growing season LAI above 3, and the regional mean for the terrestrial surfaces was 0.98. A comparison of LAI at the chamber microsites and regional mean LAI of corresponding land cover types as a whole shows that the studied plots were well representative for the whole study area (Chapter 2). Vascular LAI was recognized as a factor predicting well the spatial variability in CO₂ and CH₄ fluxes (Chapters 2 and 3). Thus, there is a high confidence that the microsites selected for the study give a complete and realistic picture of the actual spatial variability across the studied terrain.

7.3.2 Comparison of chamber and eddy covariance techniques in measuring greenhouse gas fluxes in tundra
As an intermediate step in the upscaling process from the plot to the regional scale, the results of the plot scale fluxes were compared to the landscape scale CO₂ and CH₄ fluxes measured by the eddy covariance (EC) technique. The landscape composition in the EC source area, needed for area integration of the plot scale fluxes, was estimated by footprint modeling (Chapter 2). Plot scale measurements
underestimated the gross CO₂ fluxes, but the net fluxes were in the uncertainty range of each other for the EC measuring period from late May to early October. For the growing season CO₂ balance the two measuring techniques matched very well. The plot scale measurements and the eddy covariance method agreed better on the landscape scale CH₄ emissions. This could be expected, since the spatial distribution of CH₄ emissions is much less complex than that of CO₂. Only the wet fens, willow wetlands and lakes have high CH₄ fluxes, while the emissions from the rest of the landscape are close to zero. The coverage of these land cover types was very well caught by the high-resolution QuickBird satellite image used as a basis of the land cover classification.

Since both EC and chamber methods have their advantages and disadvantages, the use of the two measuring techniques in parallel proved to be a good way to provide more sound regional flux estimates and to understand their uncertainties. Similar nested study design has been only rarely used (Soegaard et al. 2000, Zamolodchikov et al. 2003, Fox et al. 2008, Sachs et al. 2010), but can be recommended for future flux studies in order to obtain a more thorough picture of the GHG dynamics of tundra. The present work also shows that despite the criticism against the chamber method, it is very well suitable for upscaling studies in heterogeneous environments like tundra. It is the best method for studying patchy phenomena, such as the high N₂O emissions from the peat circles. Further, it allows studying the variable response of fluxes from different land cover types to environmental factors and connecting fluxes with processes.

### 7.4 RESPONSE OF SUBARCTIC TUNDRA TO CLIMATE CHANGE

When considering the climate change response of an ecosystem, it is important to separate the instant, short-term response from the long-term one. Short term climate response of an ecosystem appears as interannual variability, and can be thus understood by multiannual studies. For example, recently published EC time-series from the Arctic show that the current mean temperatures are optimal for the present vegetation, and during hot summer the sink character of the ecosystem can be reduced (Parmentier et al. 2011, Lund et al. 2012). Long-term changes, in turn, mean gradual adaptation of the ecosystem to the changed environmental conditions towards a new steady-state. For instance, a continuous positive trend in summer temperatures with more frequent hot summers would cause gradual changes in plant community composition when the ecosystem would slowly adapt to the new average conditions (e.g., Chapin et al. 1995). Based on an annual/biannual study like this one, there are only limited possibilities to predict the response of ecosystem to climate change. Nevertheless, some interpretations can still be made based on the GHG exchange at present.

In our study we observed a linear response of NEE to increased LAI (Chapter 2), meaning that better growth of vascular plants due to warming could lead to increased C sink to the studied tundra ecosystem. Here, the response of C balance is likely different in wetlands, where soil C is conserved by constantly high water tables (Chapter 3), and at drier land cover types with aerobic soils. The trend of
increased willow growth related to warming has been already observed during the last decades in Northeast European Russia (Forbes et al. 2010). In our study the willow stands were shown to be very important for the regional CO₂ and CH₄ balances and their importance will likely increase in the future. On upland tundra heath, the increased air and soil temperatures might in turn threaten the CO₂ sink character by increasing respiration (this study; Zamolodchikov et al. 2000, Heikkinen et al. 2004). Since upland tundra heath covers a large part of the study region, the changes in its GHG dynamics will impact significantly the regional C balance.

Integrative studies that combine process understanding with flux observation and incorporation of this knowledge into carbon-climate models have been suggested as a means for reducing the large uncertainty in the response of tundra C balance to climate change (McGuire et al. 2009). This kind of work is currently in progress with the Seida flux data. However, presence of permafrost adds complexity to model predictions since it is extremely difficult to predict the landscape change in future in permafrost affected terrain. Although increased coverage of wetlands at the expense of drier permafrost peatlands due to melting of permafrost has been reported from North Scandinavia and Canada (Luoto et al. 2004, Payette et al. 2004, Johansson et al. 2006), the thaw can in some cases lead to the opposite. At least for lake ecosystems drying due to enhanced subsurface water-flow following permafrost thaw has been reported (Smith et al. 2005, Jones et al. 2011). The redox conditions are very important for GHG release after permafrost thaw: For instance, C loss was 3.9 to 10 times higher in aerobic than in anaerobic conditions in thawed permafrost soils in a study by Lee et al. (2012). Similarly, Elberling et al. (2010) recognized in their incubation study the importance of drainage conditions following permafrost thaw for N₂O release from arctic soils.

Due to the contrasting GHG fluxes of different land cover types, e.g., peat plateaus with shallow active layer vs. fens with deeper seasonal thaw (Chapter 6), the changes in landscape composition will have a strong effect on the GHG balance and net radiative impact of tundra. For CH₄, increased fen coverage would mean higher emissions in the landscape scale (Chapter 3). The peat plateau coverage relative to wet fens is also crucial for the regional N₂O emissions that occur exclusively on peat plateaus. In the long term, the changes in the landscape structure will likely overrule the (more rapid) changes that will happen in the unit area fluxes of different land cover types.
7.5 SUMMARY AND CONCLUSIONS

In the following, the key findings of the study are listed:

- **Green house gas fluxes of subarctic tundra show large spatial variability in the scale of meters.** Especially for methane (CH₄) and nitrous oxide (N₂O), hot spots are important. Therefore, high resolution spatial data on fluxes and landscape composition are essential for producing realistic flux estimates in regional scale.

- **Spatial variability in carbon dioxide (CO₂) fluxes and in wetland CH₄ emissions is well explained by the leaf area index of vascular plants.** This is an easily measurable variable and can be related to remote sensing data, meaning good perspectives from the upscaling point of view.

- **Subarctic permafrost peatlands have unvegetated surfaces that, in contrast to pristine arctic soils in general, release N₂O in high amounts.** These bare peat surfaces are formed by natural processes related to the harsh climate: frost-action and wind abrasion. Sufficient drainage, a low carbon to nitrogen ratio and the absence of vegetation were identified as prerequisites for high N₂O emissions.

- **Eddy covariance and chamber techniques give similar areal green house gas exchange in subarctic tundra, offering together with remote sensing data the possibility to upscale the chamber fluxes to the regional level.**

- **The long-term climate change response of subarctic tundra will be determined by changes in the coverage of different land-cover types.** Here, one of the key factors will be permafrost distribution in peatlands that determines the relative coverage of peat plateaus vs. wet peatlands. These peatland types have contrasting fluxes with respect to all of the three green house gases.
References


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Carbon Dioxide, Methane and Nitrous Oxide Balance of Subarctic Tundra from Plot to Regional Scales

Climate warming and permafrost thaw may lead to increased emissions of greenhouse gases from northern tundra soils. In this work, fluxes of carbon dioxide, methane and nitrous oxide were studied in a subarctic tundra ecosystem. Fluxes were verified at the landscape level by comparing the results of two independent methods and then scaled up over a larger region. The results demonstrate the large heterogeneity of subarctic tundra environment with respect to the greenhouse gas fluxes. Also, a strong, previously unknown source of nitrous oxide is revealed.