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We simulated a selective cutting system through thinning of a mature mixed Norway spruce and Scots pine forest. During 2007-2016, we measured fluxes of carbon dioxide (CO_2) and methane (CH_4) with chambers and we used the eddy-covariance (EC) technique to measure CO_2 fluxes at the stand level. We established four experimental plots at a soil scarified clear-cut. Tree stumps were removed from two of these plots. During 2010-2013, we measured fluxes of CO_2, CH_4 and N_2O (nitrous oxide) with the flux-gradient technique and with chambers (CH_4) at these plots.

Forest management had clear effects on GHG fluxes. Increased soil moisture and a raised groundwater level after thinning reduced soil CH_4 uptake in the thinned stand and caused the clear-cut and stump harvested plots to switch to net sources of CH_4. Clear-cutting and stump harvesting resulted in large emissions of GHGs, but fluxes were dominated by CO_2. The degree of wetness and vegetation development had an effect on the relative contribution of the different GHGs. Stump harvesting had significant effects on CO_2 and N_2O fluxes at dry plots and the results suggest reduced mitigation potential of using stumps for bioenergy production. Substantial N_2O emissions at the dry stump harvested plot was an additional cause for concern. Thinning had an effect on both daytime uptake of CO_2 and ecosystem respiration, which resulted in reduced net CO_2 uptake at the stand level during growing seasons. On an annual basis, decreased ecosystem respiration and increased CO_2 uptake by ground vegetation had larger impacts and the net effect on annual NEE was minor.

Combined, the results presented in this thesis highlight the importance of accounting for all greenhouse gases when considering short-term effects of forest management on the climate. The results indicate that a silvicultural system that avoids net emissions of GHGs during a clear-cut phase and maintains a constant NEE might have a stronger mitigation potential than conventional even-aged forestry.

Key words: Forest management, boreal forest, clear-cutting, stump harvesting, bioenergy, eddy covariance, flux-gradient, greenhouse gas fluxes, CO_2, CH_4, N_2O

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Och hela hamnen som en spegel låg
Och såg vid såg jag såg hvarthelst jag såg
Elias Sehlstedt (Sång i Ångermanland)

List of papers

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Contributions

I. PV was involved in planning the study and contributed to the field work, the interpretation of the results and writing of the manuscript.

II. PV designed the study and performed field work, all data analyses and interpretations of the results and led the writing of the manuscript.

III. PV was involved in planning the study, contributed to the field work and data analyses and participated in writing of the manuscript.

IV. PV designed the study and performed field work, all data analyses and interpretations of the results and led the writing of the manuscript.

Abstract

Forest ecosystems cover 31% of the terrestrial land area and store large amounts of carbon in biomass and in soils. The 2015 Paris Agreement recognizes the importance of sinks and reservoirs of greenhouse gases (GHGs) in forests and the importance of enhancing them through sustainable forest management policies. Managing forests for climate mitigation purposes is, however, complex since management affects the climate and the environment in many different ways. The aim of the work presented in this thesis was to investigate and quantify short-term effects of forest management on GHG fluxes in a boreal forest in central Sweden.

We simulated a selective cutting system through thinning of a mature mixed Norway spruce and Scots pine forest. During 2007-2016, we measured fluxes of carbon dioxide (CO_2) and methane (CH_4) with chambers and we used the eddy-covariance (EC) technique to measure CO_2 fluxes at the stand level. We established four experimental plots at a soil scarified clear-cut. Tree stumps were removed from two of these plots. During 2010-2013, we measured fluxes of CO_2, CH_4 and N_2O (nitrous oxide) with the flux-gradient technique and with chambers (CH_4) at these plots.

Forest management had clear effects on GHG fluxes. Increased soil moisture and a raised groundwater level after thinning reduced soil CH_4 uptake in the thinned stand and caused the clear-cut and stump harvested plots to switch to net sources of CH_4. Clear-cutting and stump harvesting resulted in large emissions of GHGs, but fluxes were dominated by CO_2. The degree of wetness and vegetation development had an effect on the relative contribution of the different GHGs. Stump harvesting had significant effects on CO_2 and N_2O fluxes at dry plots and the results suggest reduced mitigation potential of using stumps for bioenergy production. Substantial N_2O emissions at the dry stump harvested plot was an additional cause for concern. Thinning had an effect on both daytime uptake of CO_2 and ecosystem respiration, which resulted in reduced net CO_2 uptake at the stand level during growing seasons. On an annual basis, decreased ecosystem respiration and increased CO_2 uptake by ground vegetation had larger impacts and the net effect on annual NEE was minor.

Combined, the results presented in this thesis highlight the importance of accounting for all greenhouse gases when considering short-term effects of forest management on the climate. The results indicate that a silvicultural system that avoids net emissions of GHGs during a clear-cut phase and maintains a constant NEE might have a stronger mitigation potential than conventional even-aged forestry.

Sammanfattning

Skogar täcker ca 31% av jordens landyta och lagrar stora mängder kol i biomassa och i marken. I klimatavtalet från Paris 2015 lyfts skogars roll som sänkor och reservoarer av kol fram och undertecknande länder uppmanas att implementera strategier för hållbart skogsbruk som ytterligare förstärker skogars roll som sänkor av växthusgaser. Ett aktivt skogsbruk påverkar klimat och miljö på många olika sätt och det är svårt att avgöra vilka metoder som maximerar klimatnyttan utan att nationella miljömål påverkas negativt. Syftet med de studier som ingår i den här avhandlingen har varit att undersöka korttidseffekter av olika skogsskötselåtgärder på flöden av växthusgaser mellan skogliga ekosystem och atmosfären.

I Sverige är merparten av all skog på beståndsnivå likåldriga och brukas genom s.k. trakthyggesbruk, vilket resulterar i kalhyggen. I syfte att undersöka klimatnyttan av alternativa brukningssätt simulerade vi ett s.k. kontinuitetsskogsbruk genom att gallra en slutavverkningsmogen barrskog i mellersta Sverige. Under försöket som pågick 2007-2016 mätte vi flöden av koldioxid (CO_2) och metan (CH_4) från skogsmarken med kyvetter samt flöden av CO_2 mellan skog och atmosfär på beståndsnivå med s.k. eddy-kovariansmetodik. Vi etablerade fyra mätytor på ett intilligande nytt kalhygge. På två av ytorna skördades även stubbarna i syfte att producera bioenergi. Under 2010-2013 mätte vi flöden av CO_2, CH_4 och N_2O (lustgas) på alla fyra ytor med s.k. flux-gradientteknik och kyvetter (CH_4, på två av ytorna).

De olika skogsbruksåtgärderna hade tydliga effekter på flödena av växthusgaser. Efter gallring och slutavverkning ökade markfukthalten samtidigt som grundvatten-nivån steg, vilket resulterade i ett minskat upptag av CH_4 i det gallrade beståndet och i att både slutavverkade och stubbskördade ytor övergick till att vara nettokällor av CH_4. Både slutavverkade och stubbskördade ytor var stora källor av växthusgaser men emissionerna dominerades av CO_2. Stubbskörden hade signifikanta effekter på flöden av CO_2 och N_2O på de torrare försöksytorna och resultaten antyder en reducerad klimatnytta av att använda stubbar för bioenergiproduktion. Höga N_2O-emissioner från en torr stubbskördad yta var särskilt oroande. Gallringsförsöket visade på relativt tydliga effekter på nettoutbytet av CO_2 under växtsäsongerna på grund av att upptaget av CO_2 under dagtid minskade mer än vad ekosystemrespirationen gjorde. Effekterna var fortfarande märkbara åtta år efter gallringen. På årsbasis hade den minskade ekosystemrespirationen större

genomslag, vilket ledde till att nettoutbytet av CO_2 efter gallringen låg på ungefär samma nivå som före gallringen. Ett ökat upptag av CO_2 av markevegationen efter gallringen bidrog sannolikt också till att gallringseffekten blev liten.

Sammantaget visar resultaten i den här avhandlingen på vikten av att ta hänsyn till alla växthusgaser när man utvärderar klimatnyttan av olika skogsbruksåtgärder. Resultaten antyder också att ett skogsbrukssystem som undviker stora emissioner av växthusgaser under kalhyggesfasen och som upprätthåller ett högt nettoupptag av CO_2 kan ha betydligt högre klimatnytta än konventionellt trakthyggesbruk.

Content

Introduction

Forests, forestry and climate change

Forests cover almost four billion ha globally, which is equivalent to 31% of the total land surface area (Keenan *et al.*, 2015). Since 1990, there has been a decrease of 3% of forested area globally, but the net rate of forest loss has slowed down recently (Keenan *et al.*, 2015; Sloan and Sayer, 2015). Boreal forests cover approximately 1.22 billion ha and have shown a slightly increasing trend in land area coverage since 1990 (Keenan *et al.*, 2015). Boreal forests have been estimated to hold 272±23 Pg C in biomass (live and dead) and soils, which is approximately 32% of the global forest stocks of carbon (Pan *et al.*, 2011) and about 30% of the carbon in the atmosphere.

Through photosynthesis, forests sequester atmospheric carbon dioxide (CO_2) and the global sink of carbon in forests has been estimated to be 2.4±0.4 Pg C year^{-1} on average for the period 1990-2007, where boreal forests were estimated to contribute 0.5 ±0.08 Pg C year^{-1} to the total forest sink (Pan *et al.*, 2011). However, this sink in global forests is counteracted by carbon losses from deforestation and land-use change in mainly tropical regions, resulting in a net global forest sink of 1.1±0.8 Pg C year^{-1} (Pan *et al.*, 2011). Recently, Le Quéré *et al.* (2016) estimated total CO_2 emissions from fossil fuels and cement production during the period 2006-2015 to be 9.3±0.5 Pg C year^{-1}, and thus, the gross CO_2 uptake of forests mitigate approximately 25% of the anthropogenic CO_2 emissions. It has been proposed that forests have an even larger climate change mitigation potential through forest management and proper use of forest products (e.g. Canadell and Raupach, 2008).

The 2015 Paris Agreement recognizes the importance of sinks and reservoirs of greenhouse gases (GHGs) and the importance of enhancing them. Article 5 of the agreement specifically emphasizes the importance of forests and encourages signatories to implement sustainable forest management policies (UNFCCC, 2016). However, forest management for climate change mitigation purposes is complex and not straight-forward since it affects the climate and the environment in many different, often interconnected, ways through its impact on biogeochemical processes (e.g. GHG exchange between forests and the atmosphere) and through biophysical effects such as changes in surface reflectivity (albedo) and energy exchange. Naudts *et al.* (2016) showed that 250 years of management of Europe's forests have had a net warming effect on the climate, mainly because of conversion of broadleaved forests into conifer forests, wood extraction (and related changes in carbon stocks in biomass and soils) and afforestation. It has also been shown that carbon stocks generally are lower in managed forests, that managed forests are considerably younger and more often contain coniferous stands than unmanaged forests do (Noormets *et al.*, 2015).

Since the 1970s, bioenergy production has increased steadily in Sweden. Today, about one third of Sweden's total energy supply originates from biomass. About half of the bioenergy production is based on biomass from forests (Swedish Energy Agency, 2015). Due to international, as well as national, climate change mitigation strategies applied in Sweden, the demand of forest biomass is expected to increase further (Börjesson *et al.*, 2017). Increased extraction of biomass from forests have potential impacts on long-term productivity of forests, biodiversity, soil and water chemistry, carbon and nutrient pools etc. Recently, de Jong *et al.* (2017) estimated that extraction of harvest residues (e.g. tree tops, branches, stumps) from forests could increase by a factor of 2.5 without jeopardizing sustainability goals. However, the authors also pointed out that more stump harvesting experiments are needed to properly assess effects on productivity and on leaching of nitrogen and mercury following stump harvest and highlighted the importance of long-term field experiments (existing and new) at sites with different soil properties, forest cover and climatic conditions.

Nonetheless, the climate benefit of using forest biomass for bioenergy has been questioned. Schulze *et al.* (2012) pointed out that large-scale bioenergy production using forests biomass results in direct CO_2 emissions that would counteract climate change mitigation goals on decadal time scales and that it would result in depleted carbon pools, younger forests, decreased soil nutrient pools and only a small, if any, reduction in GHG emissions. Hudiburg *et al.* (2011) reported that the carbon sink strength of managed forests in Oregon, USA, was larger than the effect of substituting fossil fuels with energy produced from biomass from these forests. Zanchi *et al.* (2012) showed that the assumption of zero GHG emissions from bioenergy production is not correct and that the time perspective has to be considered. The use of harvest residues and biomass from bioenergy plantations had almost direct climate benefits (when compared to fossil fuels), while the use of other woody biomass for bioenergy production would not contribute to reduced GHG emissions within the time perspective of decades. Increased harvest intensity with the aim to produce more bioenergy had negative climate impacts in the short- to medium term time perspective (Zanchi *et al.*, 2012).

In addition, Zenone *et al.* (2016) studied GHG exchange in a short-rotation poplar plantation, planted for bioenergy production, and found that the net uptake of CO_2

was offset by large emissions of methane (CH_4) and nitrous oxide (N_2O). During the four-year study, the short-rotation plantation was a net source of 1.90±1.37 Mg ha^{-1} of CO_2-equivqlents, with equal contributions from CH_4 and N_2O, but where almost half of the emitted N_2O came from a single emission peak relatively soon after conversion to a short-rotation bioenergy plantation.

Sustainable forest management policies should also consider impacts on biodiversity, ecosystem services and socioeconomics. At the same time, management strategies resulting in changed forest structure and composition and in more standing biomass could also result in forests more susceptible to storm damages, insect attacks and fire, especially in a future, warmer world with possibly more climate extremes (e.g. Seidl *et al.*, 2011a; Seidl *et al.*, 2011b). It is clear that forest management for mitigation purposes requires detailed knowledge of forests and the complex web of interconnected ecological, biogeochemical and biophysical processes that are affected by disturbances to forest ecosystems.

The focus of this thesis is on the short-term effects of forest management on greenhouse gas exchange.

Effects of forest management on greenhouse gas fluxes

In Sweden, and in the boreal region as a whole, the dominating silvicultural method is even-aged forestry. Following clear-cutting, the soil is typically scarified to enhance survival and growth of the seedlings that are planted. This is often followed by a pre-commercial thinning and one to three thinnings before the stand is clear-cut again. Typical rotation periods in Sweden are 60-120 years but can be both shorter and longer. During 2004-2013, an average of 195 600 ha was clear-cut annually in Sweden. Approximately 88% of this area was soil scarified and approximately 83% of the area was planted. During the same time period, an average of 367 600 ha was pre-commercially thinned and 344 500 ha were thinned each year (Swedish Forest Agency, 2017).

Extraction of wood from forests may have many consequences for both climate and environment but to what extent depends on harvest intensity, the severity of soil disturbance, ecosystem type, soil properties and vegetation development in the disturbed forest stand, among other things. Removal of trees results in reduced photosynthesis, reduced autotrophic respiration and increased heterotrophic respiration and thus, has a large impact on the CO_2 budget of a managed forest stand. In addition, removal of the trees also reduces transpiration, which may result in a raised groundwater level in the stand, depending on harvest strength and on soil properties. Apart from possible effects on the CO_2 budget, this might also affect production and consumption of the powerful greenhouse gases CH_4 and N_2O.

Methane is about 28 times more effective as a greenhouse gas than CO_2 in a 100-year perspective (i.e., it has a so-called Global Warming Potential, GWP_{100}, of 28) and is 84 times as effective as CO_2 in a 20-year perspective (GWP_{20}=84) (Myhre *et al.*, 2013). Nitrous oxide has the global warming potentials of 265 (GWP_{100}) and 264 (GWP_{20}), respectively (Myhre *et al.*, 2013). These values of GWP_{20} and GWP_{100} for CH_4 and N_2O do not included any climate-carbon feedback effects (see Myhre *et al.* (2013) for definition) and hence, it is a conservative estimate of the relative forcing effects of CH_4 and N_2O on the climate system.

Total global emissions of CH_4, of natural and anthropogenic origin, have been estimated to approx. 550 Tg year^{-1} of CH_4 and have thereby contributed approximately 20% to the observed warming of the atmosphere (Kirschke *et al.*, 2013). Recently, Tian *et al.* (2016) used two different approaches for estimating the global biogenic emissions (i.e., of biological origin) of CH_4 and found it to be between 433±52 and 435±57 Tg year^{-1} of CH_4 during the period 2001-2010. Natural wetlands were the largest terrestrial biogenic source and contributed 40-50% to the total biogenic emissions during 2001-2010, while biomass burning contributed 4-5% (Tian *et al.*, 2016).

Removal of atmospheric CH_4 mainly takes place through chemical processes in the troposphere and the stratosphere (mainly through oxidation by hydroxyl radicals) and through oxidation by methanotrophic bacteria in aerated soils. (e.g. Ehhalt, 1974; Kirschke *et al.*, 2013). Soils are generally sinks of atmospheric CH_4 (Smith *et al.*, 2000) and the sink strength has been estimated to be between ~4% (Kirschke *et al.*, 2013) and ~10% (Tian *et al.*, 2016) of the total global CH_4 sink. Dutaur and Verchot (2007) reported the largest sink strength of forest soils, which indicates that the global CH_4 budget could be sensitive to disturbances to forest soils.

Through microbial decomposition of organic matter by *Archaea*, CH_4 is produced in water-saturated, anaerobic parts of the soil (Ehhalt, 1974) and at anaerobic microsites within otherwise aerobic soils (von Fischer and Hedin, 2002). Changes in hydrology following harvesting of trees (a raised groundwater table and/or increased soil moisture) might result in decreased net uptake of CH_4, or even cause a forest stand to switch from being a sink of atmospheric CH_4 to being a net source (Castro *et al.*, 2000; Zerva and Mencuccini, 2005).

Soil disturbance, caused by forest management operations, might also influence production and/or consumption of CH_4 through its impact on soil properties and soil conditions. Teepe *et al.* (2004) reported decreased CH_4 consumption following compaction of the soil by heavy machinery and Mojeremane *et al.* (2012) found increased CH_4 emissions where soil scarification (mounding) had increased soil bulk density. Strömgren *et al.* (2016) found significant emissions of CH_4 from soil pits and wheel ruts after clear-cutting and stump harvesting.

The total biogenic emissions of N_2O were recently estimated to be between 19.8±1.1 and 23.9±1.6 Tg year^{-1} of N_2O (Tian *et al.*, 2016) and where soils in natural ecosystems, agricultural soils and biomass burning contributed 55-60%, 25-30% and ~5%, respectively (Tian *et al.*, 2016). Thus, soils are a dominating source of atmospheric N_2O. Nitrous oxide has contributed approximately 6% to the observed warming of the atmosphere (Butterbach-Bahl *et al.*, 2013).

Although a multitude of biotic and abiotic pathways for N_2O formation in soils exists, N_2O production mainly takes place through microbe-mediated processes (i.e., nitrification, denitrification, nitrate ammonification and nitrifier denitrification) (Butterbach-Bahl *et al.*, 2013). Approximately 70% of the global emissions of N_2O from soils derives from two main processes; nitrification and denitrification (Butterbach-Bahl *et al.*, 2013). These processes are regulated from cellular level to microsite level to landscape level by a multitude of coupled variables and interactions between soils, vegetation and climate (Firestone and Davidson, 1989). While the availability of reactive nitrogen in soils is a key driver of N_2O production in general, soil moisture has a strong influence on denitrification because it regulates available oxygen for soil microbes. Denitrification is also sensitive to temperature and is tightly coupled to the microbial carbon cycle in soils (increased soil respiration in response to warming may result in increased nitrogen availability and in decreased O_2 concentrations in soils, which favors denitrification). For a more complete review of processes regulating N_2O production, see Butterbach-Bahl *et al.* (2013) and references therein.

However, N_2O can also be reduced to N_2 in soils through denitrification (e.g. Bremner, 1997) and through nitrifier denitrification (e.g. Poth, 1986; Schmidt *et al.*, 2004) and thereby result in decreased emission rates or, under certain circumstances, in net uptake of atmospheric N_2O in soils. Net N_2O uptake has been observed in different ecosystem and with different measurement techniques (e.g. Ryden, 1981; Schiller and Hastie, 1996; Klemedtsson *et al.*, 1997; Butterbach-Bahl *et al.*, 2002; Pihlatie *et al.*, 2005; Eugster *et al.*, 2007; Mammarella *et al.*, 2010). Chapuis-Lardy *et al.* (2007) reviewed available literature and concluded that it was not possible to pinpoint a clear set of soil conditions (e.g. pH, soil temperature, soil moisture, soil nitrogen availability, O_2 content etc.) favoring N_2O consumption but found that net N_2O uptake was often reported in connection with low mineral nitrogen content and low oxygen availability in the soils.

Production and consumption of N_2O takes place simultaneously in soils and are regulated by complex interactions between processes and variables operating at different spatial scales, from microsites to landscape level (Firestone and Davidson, 1989) and the resulting net N_2O fluxes between soils and the atmosphere are highly variable in space in time (e.g. Groffman *et al.*, 2009; Butterbach-Bahl *et al.*, 2013). This might be especially true in a disturbed forest ecosystem where soil disturbance caused by forest operations enhances the spatial variability of soil properties and conditions. Although chamber measurements can help to gain detailed understanding of N_2O fluxes, responsible production/consumption processes and drivers thereof at a small spatial scale, quantification of net fluxes of N_2O at the ecosystem level following forest management operations requires measurement techniques that integrate fluxes over larger spatial scales. Furthermore, in order to track temporal changes of N_2O fluxes and to derive robust annual N_2O budgets, continuous measurements are required (Merbold *et al.*, 2014).

Clear-cutting and soil scarification

To fully understand GHG dynamics and the net effects of clear-cutting on the climate, the environment, future biomass production etc., one would need detailed measurements throughout, at least, one rotation period and preferably several rotation periods. While this might be a viable alternative in short-rotation bioenergy plantations, it is not, for obvious reasons, an alternative for boreal coniferous forests.

Long-term measurements of net ecosystem exchange (NEE) of CO_2 at clear-cut sites are rare. Coursolle *et al.* (2012a) used the eddy covariance (EC) technique to follow the recovery of NEE at the stand level after clear-cutting of a black spruce (*Picea mariana*) forest stand in Canada and found that the stand reached carbon neutrality (when uptake of CO_2 equals losses through respiration, on an annual basis) after 10 years. In lack of long-term measurements, it is possible to use forest chronosequences, i.e., the same type of forests growing under similar conditions (regarding soil properties, climatic conditions etc.) and that are managed in similar ways but are of different ages (from fresh clear-cuts to mature forests), to study time-dependent development of forests and of processes of interest. Coursolle *et al.* (2012b) studied six chronosequences (whereof three were harvest chronosequences) in Canada and found that boreal forests, on average, reached carbon neutrality 9 years after the initial disturbance and that losses during these 9 years were offset after 26 years. However, two of the harvest chronosequences indicated that it took 14 and 18 years to reach carbon neutrality and that it took 34 and 47 years, respectively, to offset initial carbon losses. Amiro *et al.* (2010) studied North American chronosequences, covering a wide range of forests and disturbance types, and found indications of net CO_2 emissions for about 10 years following a stand replacing disturbance in boreal forests and that it took another 10 years to offset initial losses. Lindroth *et al.* (2009) combined data from four European chronosequences (Kowalski *et al.*, 2003; Lindroth *et al.*, 2003; Kolari *et al.*, 2004; Kowalski *et al.*, 2004) and found that harvested forests reached carbon neutrality after about 15% of the relative stand age (stand age divided by typical rotation period for each chronosequence), which correspond to approximately 9-18 years for typical rotation periods in even-aged forestry in Sweden (60-120 years). The initial losses were offset after 25-30% of the relative age, i.e., in the span 15-18 years to 30-36 years for typical rotation periods in Sweden.

While EC measurements of CO_2 fluxes in clear-cut boreal forest are rare, there are no studies available at all when it comes to simultaneous micrometeorological measurements (e.g. EC or flux-gradient) of CO_2, CH_4 and N_2O. However, Mishurov and Kiely (2010) measured N_2O fluxes on recently afforested grassland and found increased N_2O emissions related to mechanical disturbance of the soil. Others have reported EC measurements of N_2O (Zona *et al.*, 2013b), CO_2 and CH_4 (Gao *et al.*, 2015) or CO_2, CH_4 and N_2O (Zona *et al.*, 2013a) from poplar plantations, also this on afforested land.

Through chamber measurements, it is possible to gain detailed insight into fluxes from small, well-defined source areas and to unravel which the main drivers of the fluxes are. Chamber measurements are, however, labor-intensive and often hampered by poor spatial and temporal resolution, which makes it hard to upscale fluxes to stand level and to derive reliable estimates of long-term GHG budgets (Butterbach-Bahl *et al.*, 2013). Nonetheless, chambers have been used for measurements of CO_2 fluxes from the soil following harvest (e.g. Gough *et al.*, 2005; Misson *et al.*, 2005; Dore *et al.*, 2014; Mjöfors *et al.*, 2015; Webster *et al.*, 2016; Strömgren *et al.*, 2017). Chambers have also been used at clear-cuts for measurements of CH_4 (e.g. Saari *et al.*, 2004; Wu *et al.*, 2011), N_2O (e.g. Saari *et al.*, 2010; McVicar and Kellman, 2014) and of different combinations of these GHGs (e.g. Schiller and Hastie, 1996; Huttunen *et al.*, 2003; Zerva and Mencuccini, 2005; Saari *et al.*, 2009; Lavoie *et al.*, 2013; Kulmala *et al.*, 2014; Peichl *et al.*, 2014; Strömgren *et al.*, 2016).

While it is hard to generalize the results from these chamber studies in very different forest types, with differences in climatic conditions, disturbance history, management, soil properties etc., it is possible to find some common responses to clear-cutting, and some differences, in the Fennoscandian studies with similar conditions (i.e., Strömgren and Mjöfors, 2012; Kulmala *et al.*, 2014; Mjöfors *et al.*, 2015; Strömgren *et al.*, 2016; Strömgren *et al.*, 2017).

Kulmala *et al.* (2014) reported increased soil respiration after clear-cutting of a mature (100 year) Norway spruce (*Picea abies*), as compared to a non-harvested mature forest, in southern Finland. The CH_4 uptake decreased following clear-cutting but was not significantly different from the control. However, no soil scarification was performed at the clear-cut and harvest residues were left on site. Strömgren *et al.* (2017) investigated the impact of commonly used soil scarification methods on fluxes of CO_2 at 14 clear-cut forest stands (ten Norway spruce stands, two Scots pine stands and two mixed Norway spruce and Scots pine stands) along a latitudinal gradient in Sweden. Although fluxes differed between sites and between treatments, the general conclusion was that soil scarification did not enhance CO_2 emissions as compared to controls. Fluxes were, on average, lower or equal to fluxes at control plots. These results were in line with other recent studies on the effects of soil scarification om CO_2 fluxes in Sweden (Strömgren and Mjöfors, 2012; Mjöfors *et al.*, 2015).

At three of the abovementioned sites, Strömgren *et al.* (2016) also investigated fluxes of CH_4 and N_2O for two years following clear-cutting and soil scarification. While both fluxes of CH_4 and N_2O were significantly affected by disturbance, the magnitude varied between sites and between disturbance classes (i.e., intact soil, soil pits, mounds, mixed soil and wheel-ruts). Emissions of CH_4 were found from wheel-ruts at all sites but otherwise there were net uptake of CH_4 at all other disturbance classes. The N_2O fluxes were highest from soil pits and mixed soil at one site, highest from intact soil and mounds at a second site insignificant from all classes at the third site. When fluxes of CH_4 and N_2O were upscaled to stand level based on the spatial coverage of each disturbance class, there were no significant differences between soil scarified plots and control plots in either year. Strömgren *et al.* (2016) also expressed fluxes of CH_4 and N_2O as CO_2-equivalents (using GWP_{100} factors of 34 and 298, respectively) and found that the contribution of CH_4 to the GHG budgets at these site were in the order of 0.0-0.2%, while N_2O contributed 0.1-8%, depending on site and year. In an afforestation study in northeast England, Mojeremane *et al.* (2012) found increased CH_4 emissions and decreased N_2O emissions from soil scarified (mounded) plot as compared to control plot. The net effect of mounding on the GHG budget was lower emissions (expressed as CO_2-equivalents) the first year and similar emissions the second year.

Thinning/selective cutting

Considering the long time it takes to reach carbon neutrality and to offset the initial losses of carbon following clear-cutting, the question if other management strategies can avoid the initial losses of carbon and result in maintained timber production and maintained, or even increased, net ecosystem productivity arises. Potentially, a system with selective cutting of trees in uneven-aged forest stands could be an alternative, with the possibly added benefits of maintaining ecosystem services, biodiversity and recreational values

A selective cutting system requires uneven-aged forests, i.e., forests with trees of all sizes and ages, from seedlings to full-sized trees, distributed throughout all parts of the forest. It also requires that natural regeneration is sustained and that the new seedlings survive and eventually reach the canopy layer. It is generally assumed that a sustainable natural regeneration in Fennoscandia is only achieved in Norway spruce forests (Lundqvist, 2017), i.e., in forests dominated by shade-tolerant species. Recently, Brockway and Outcalt (2017) reported successful natural regeneration of longleaf pine (*Pinus palustris*) on upland soils in southeastern USA following different selective cutting strategies (single tree selection, group selection and different varieties of shelterwood). Although standing biomass volume decreased in all treatments, annual growth rates were normal (1-5% per year) and comparable to control plots.

Important aspects to consider in uneven-aged forestry is future production, which is dependent on not only natural regeneration but also on trees of all age and size classes already present in the system (Lundqvist, 2017). Traditional forest management in even-aged forest stands is based on assessments of current volume growth and mean volume growth. The current volume growth is zero directly after clear-cutting but increases fast and reaches maximum at a young stand age and slowly decreases over the rest of the rotation period, while the mean volume growth increases steadily throughout the rotation period. Maximum long-term production of the forest stand is achieved when the current volume growth equals mean volume growth and the stand is normally clear-cut around that age. In uneven-aged forest stands managed through selective cutting, the current volume growth could theoretically be constant over time, and equal to the mean volume growth (Lundqvist, 2017).

Lundqvist (2017) reviewed available literature on selective cutting of Norway spruce forests in Fennoscandia and concluded that a management practice that maintains a large standing volume through moderate harvest strengths focusing on removing the largest trees at relatively short intervals results in a relatively high volume growth, reaching 80-90% of the volume growth in even-aged forestry. However, this conclusion were based on relatively few studies, and where many of the uneven-aged stands had been managed in non-optimal ways. Nilsen and Strand (2013) compared even-aged and uneven-aged Norway spruce stands after 81 years of selective cutting and traditional even-aged forestry (with five thinnings during the period). While the present carbon storage in standing biomass was considerably higher in the even-aged stand, the soil carbon stock was higher in the uneven-aged stand and the long-term timber production was 95% of that in the even-aged stand. Clarke *et al.* (2015) reviewed available literature on the effects of harvesting intensity on soil carbon stocks in boreal and temperate forests and found contrasting results of thinning, ranging from increased to decreased soil carbon content and where several studies reported no significant changes. Effects of selective cutting on soil carbon stocks suggested either no effect or increased soil carbon stocks. The number of studies were few and should be interpreted cautiously.

Recently, Lagergren and Jönsson (2017) simulated the effects of climate change and forest management on e.g. harvest levels, net income, storm resistance and carbon pools. Different management schemes were applied to even-aged forestry and continuous cover forestry (selective cutting), which were then compared to unmanaged forests. The results showed that unmanaged forest stored more carbon than managed forests did. The highest annual harvests were in even-aged pine forests and in stands managed through selective cutting. The latter also generated the highest net income but were found to have the lowest storm resistance. One conclusion from the study was that it might require a combination of management strategies at the landscape level to optimize ecosystem services of forests.

Lundmark *et al.* (2016) compared the long-term effects on growth and yield of selective cutting to conventional even-aged forestry using a set of models. The starting point was even-aged forest stands of Norway spruce on soil with average fertility. Two scenarios with assumed long-term production levels of 80% and 100% of that in conventional even-aged forestry was compared with two scenarios of clear-cutting (removals of stems only and removal of stems, stumps and harvest residues). The findings were very similar biomass production (~4.65 Mg $ha^{-1}year^{-1}$ of dry biomass) in all scenarios assuming the same production level and slightly higher annual biomass extraction from the selective cutting scenario with 100% production level than in the normal clear-cutting scenario (removal of stems only) (2.54 vs. 2.18 Mg $ha^{-1}year^{-1}$ of dry biomass). One main conclusion was that biomass growth and yield was more important than the silvicultural system chosen. However, the study assumed the same response of soil carbon dynamics in all scenarios and did not include changes in soil carbon stocks. Annual litter carbon input, although small in absolute terms, were 2-5 times higher in the selective cutting scenarios than in the clear-cutting scenarios.

Thus, recent studies on selective cutting systems have focused on regeneration, production, and to some extent on effects on soil carbon pools. I am not aware of any studies on how NEE at stand level would be affected by selective cutting of uneven-aged forest stands. However, studies of NEE following conventional thinning in even-aged stands might provide useful information and give indications on whether or not selective cutting strategies could be a viable alternative to even-aged forestry. The few studies available that have measured whole ecosystem NEE using the eddy covariance technique following thinning all point in the same direction, to insignificant or short-lived effects on NEE regardless of forest type; temperate deciduous forests (Granier *et al.*, 2008; Wilkinson *et al.*, 2016); temperate conifer forests (Dore *et al.*, 2012; Saunders *et al.*, 2012); boreal conifer forest (Vesala *et al.*, 2005). Several of the studies attributed the lack of significant effects on NEE to increased photosynthesis of remaining trees and/or ground vegetation (Vesala *et al.*, 2005; Granier *et al.*, 2008; Saunders *et al.*, 2012; Wilkinson *et al.*, 2016).

The effects of thinning and selective cutting on soil respiration has been studied with the soil chamber method in several studies. Some studies reported small or insignificant effects on soil respiration following selective cutting of temperate deciduous forests (Stoffel *et al.*, 2010; Shabaga *et al.*, 2015). Laporte *et al.* (2003) found limited effects on soil respiration from a selectively cut temperate deciduous forests in Canada but respiration was significantly lower from disturbed microsites. Sullivan *et al.* (2008) reported decreased soil respiration the first year after restoration thinning (aiming at removing dense groups of small diameter trees) of a ponderosa pine forest in Arizona, USA, previously managed through selective cutting.

In addition, Sullivan *et al.* (2008) found no effects of the restoration thinning on soil CH_4 exchange and the authors attributed this to the low level of disturbance to the forest floor. Wu *et al.* (2011) found decreased uptake up CH_4 following clearcutting of a Norway spruce forest while CH_4 exchange was not affected by selective cutting. Dannenmann *et al.* (2007) studied the effects of thinning on fluxes of CO_2, CH_4 and N_2O in three temperate deciduous forests and found no significant effect on any of the GHGs at one site, reduced CH_4 uptake at the second site and clear effects on all GHGs at the third site, with significantly increased N_2O emissions being the most pronounced effect.

Stump harvesting and soil scarification

Due to uncertainties regarding environmental impacts, tree stumps have not yet been harvested at a larger scale in Sweden (Persson, 2016). Initially, recommendations from the Swedish Forestry Agency (Swedish Forest Agency, 2009) set an upper limit for stump harvesting at 20000 ha year^{-1} in Sweden. The annually harvested area increased steadily from 2005 to 2010, when the harvested area peaked at approximately 7500 ha year^{-1} (Swedish Forest Agency, 2017). Recently, the effects of stump harvesting on stand productivity (e.g. Egnell, 2016; Jurevics *et al.*, 2016), nutrient leaching (e.g. Eklöf *et al.*, 2012; Bergholm *et al.*, 2015; Palviainen and Finér, 2015), mercury leaching (e.g. Eklöf *et al.*, 2012; Eklöf *et al.*, 2013), biodiversity (e.g. Tarvainen *et al.*, 2015; Kataja-aho *et al.*, 2016; Rudolphi and Strengbom, 2016) and climate change mitigation potential (e.g. Ortiz *et al.*, 2016) has been extensively studied.

The effects of stump harvesting on soil carbon pools in the short-term (8-13 years) (Hyvönen *et al.*, 2016) to medium-term (20-39 years) (Karlsson and Tamminen, 2013; Strömgren *et al.*, 2013; Jurevics *et al.*, 2016; Persson *et al.*, 2017) perspective have also been studied. Although some studies found higher carbon content in the mineral soil and lower carbon content in the organic layers, which suggests a re-distribution of carbon as a consequence of the stump harvesting, no significant effects were found on total carbon pools. The minor effects on total soil carbon pools suggest that stump harvesting only has direct effects on soil respiration (i.e., lower soil respiration because of the removal of the stumps) and no, or only minor, indirect effects (i.e., increased soil respiration as a consequence of the disturbance and mixing of organic and mineral soil horizons).

There have been concerns that the heavy soil disturbance during stump harvesting could enhance soil respiration and emissions of GHGs and thereby reducing or even cancelling the potential climate benefits of using stumps for bioenergy production. To date, there is only one study available that have used continuous EC measurements of net CO_2 fluxes at stand level after stump harvesting and soil scarification. During the first year of the study, Grelle *et al.* (2012) found lower emissions of CO_2 at a stump harvested and soil scarified plot than at the soil scarified control plot (when modeled decomposition of the stumps were subtracted from the data). This indicates a direct effect only, i.e., no extra emissions of CO_2 from the soil following disturbance. However, during the following years, there was an increasing trend in CO_2 emissions and after three years, emissions were similar at the stump harvested plot and the control plot. This indicates an indirect effect of the same magnitude as the (avoided) stump decomposition and thus, reduced climate mitigation potential of stumps. The results of Grelle *et al.* (2012) also indicates that the (expected) indirect effects may occur with a time-delay not captured in short-term (1-2 years) studies. Recent chamber studies on CO_2 fluxes from soils after stump harvesting and/or soil scarification found no, or only minor, effects on soil respiration compared to control plots (Strömgren and Mjöfors, 2012; Mjöfors *et al.*, 2015; Uri *et al.*, 2015; Strömgren *et al.*, 2017). However, no differences between treatments indicates an indirect effect, of equal magnitude as the (avoided) decomposition of the stumps.

The effects of stump harvesting on CH_4 and N_2O fluxes at clear-cut boreal forest stands are less studied. Strömgren *et al.* (2016) studied three stump harvested and soil scarified clear-cuts in central Sweden and found substantial CH_4 emissions from wheel-ruts and soil pits created by the stump extraction and high emissions of N_2O from pits and mounds at a site with high nitrogen availability. When scaled to plot level according to the area covered by each disturbance class, no significant differences were found between treatments and the contributions of CH_4 and N_2O to the total GHG budgets were low (0.0-0.2% and 0.1-8%, respectively).

Aims and objectives

Although forest ecosystems and many different aspects of forest management have been extensively studied, surprisingly little is known about how forests should be sustainably managed for maximizing climate mitigation benefits at the same time as the supply of wood and fiber are maintained, and without negative consequences for the environment and humans.

The overarching aim of the work leading up to this thesis has been to quantify the effects of different forest management practices on greenhouse gas fluxes using different measurement techniques. Extra emphasis was placed on developing and using a flux-gradient system that facilitated continuous multi-plot measurements of CO_2, CH_4 and N_2O fluxes and allowed for robust inter-plot comparisons.

The specific objectives were:

- To quantify how CH_4 exchange between the forest floor and the atmosphere is affected by thinning, clear-cutting and stump harvesting in comparison to an undisturbed mature forest (Paper I).
- To investigate and quantify spatial and temporal dynamics of greenhouse gas fluxes and estimate full greenhouse gas budgets following clear-cutting and soil scarification (Paper II).
- To investigate if selective cutting could be a feasible alternative to even-aged forestry from a climate perspective by simulating selective cutting through thinning from below in a mature coniferous forest (Paper III).
- To investigate and quantify spatial and temporal dynamics of greenhouse gas fluxes and to estimate full greenhouse gas budgets following stump harvesting and soil scarification as compared to clear-cut and soil scarified control plots (Paper IV).

Material and Methods

Site description

All measurements took place in a hemiboreal forest at the research station Norunda in central Sweden (60˚5′ N, 17˚29′ E). The station was established in 1994 and is today a part of the Swedish ICOS network (http://www.icos-sweden.se/). The forest surrounding the station was a mixture of stands of different ages and different management histories. Within one km radius of the main flux tower, stands varied in ages from 0-120 years and consisted of a mix of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and a smaller fraction birch (*Betula sp.*). Within a 500 m radius, the stands were rather homogeneous with tree heights of 25-28 m. The soil was a sandy-loamy glacial till, highly heterogeneous and rich in stones and blocks (Lundin *et al.*, 1999), overlain with a thin (3-10 cm) organic layer. Ground vegetation was dominated by bilberry (*Vaccinum myrtillus*), lingonberry (*Vaccinium vitis-idaea*), feathermosses (*Hylocomium splendens* and *Pleurozium schreberi*) and grasses, depending on stand. Mean annual air temperature was 6.5°C and mean annual precipitation was 576 mm (average for the period 1980-2010 in Uppsala, 30 km south of Norunda).

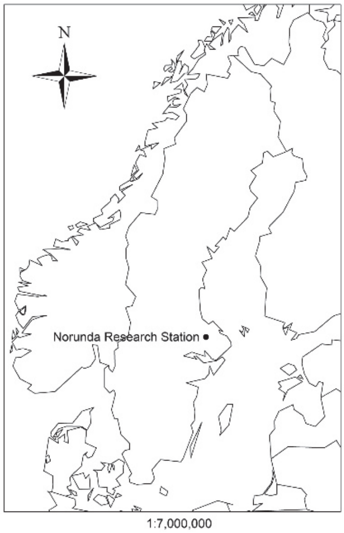

Figure 1. The Norunda research station in central Sweden.

In November 2008, a part of the forest was thinned from below in order to simulate continuous cover forestry with a selective cutting system. The thinning reduced the amount of smaller spruce trees and favored larger pine trees with well-developed canopies. The thinned area had the shape of a semicircle with a radius of 200 m, with the flux tower at the origin of the diameter. In addition, along the access road, a rectangular strip (35x400 m) was thinned in the same way (Figure 2). In 2008, the thinned stand was approximately 100 years old. The thinning reduced tree density from 857 stems ha^{-1} to 429 stems ha^{-1} while the basal area was reduced by 21%.

In early 2009, a new clear-cut was established outside of the 500 m radius of the main tower (Figure 2). The total clear-cut area was approximately 30 ha but several large areas were left for nature conservation purposes in stands, or parts of stands, with soils classified as moist or wet. In addition, there were also areas where widely spaced seed trees (pine) were left for natural regeneration. The stand where the GHG measurements took place was classified by the forest owner as mesic.

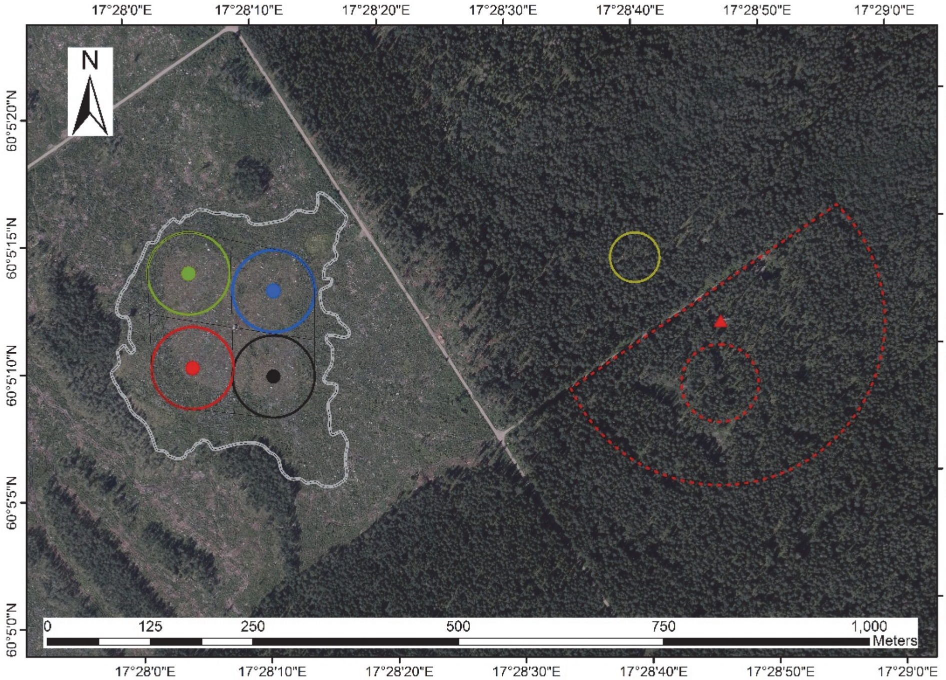

Figure 2. GSD-Ortophoto of the Norunda forest in central Sweden © Lantmäteriet (Swedish Surveying and Cadastal Agency). The red dashed semicircle marks the area that was thinned in 2008. The red triangle marks the position of the 102 m tall flux tower. The red dashed circle marks the area where chamber measurements and below-canopy EC fluxes were measured. The yellow circle marks the area where chamber meauserments were made in undisturbed forest. The solid circles at the clear-cut marks the clear-cut plots (black: wet; red: dry) and the stump harvested plots (blue: wet; green: dry). The grey line represents the outer border of the area where all trees were removed in 2009.

Four experimental plots were established at a part of the clear-cut where all trees had been removed. Harvest residues were left at all plots. In May 2010, all the experimental plots were soil scarified (mounded) and at two of the plots, the stumps were also harvested for bioenergy production. About 22% of the stumps remained after harvesting at these plots. All plots were planted directly following stump harvesting and soil scarification (about 2500 seedlings ha^{-1} (50% Norway spruce and 50% Scots pine). An additional 2200 seedlings ha^{-1} (100% Norway spruce) were planted in May 2012 to compensate for the poor survival of the seedlings planted in 2010.

Due to small differences in topography, and possibly due to differences in soil properties, one plot of each treatment (i.e., clear-cutting and soil scarification, and stump harvesting and soil scarification) were considerably wetter than the other two plots. This means we had one wetter and one drier plot of each treatment.

Chamber measurements

An automated chamber system with six transparent chambers standing on pre-installed stainless steel collars were used for quantifying the effect of thinning on soil CO_2 fluxes (2008-2009; Paper III) and the effect of thinning, clear-cutting and stump harvesting on soil CH_4 fluxes (2009-2010; Paper I). The chambers had a volume of 0.11 m^3 and covered a surface area of 0.2 m^2 (Figure 3). During the soil respiration measurements, a non-dispersive infrared gas analyzer (LI-820, LI-COR Inc. NE, USA) was used while a high-precision laser gas analyzer (DLT-100, Los Gatos Research, CA, USA) was used for measurements of CH_4 exchange. A small fan ensured sufficient mixing of air in the chambers during measurements. Soil temperature, soil moisture and PAR were measured in all chambers.

The gas exchange between the forest floor and the atmosphere was calculated using the slope of a linear regression of gas concentration data (dC/dt) following chamber closure. For CO_2 measurements (Paper III), the first 30 s were discarded and concentration data from 30 to 180 s were used for the calculations. For the CH_4 measurements (Paper I), 120 s of data were used, starting directly following chamber closure. Five slopes, each lagged by 10 s, were evaluated and the slope with the highest r^2 was kept for calculations of CH_4 exchange. In both cases (Paper I and III), only data where the r^2 were higher than 0.3 (the limit for when fluxes were significantly different from zero) were kept for further analysis. The gas flux F_C was calculated as $F_c = dC/dt \cdot V/A$ where C (µmol m^{-3}) is molar density (of CO_2 or CH_4), V (m^3) is the total chamber and collar volume and A (m^2) is the surface area covered by the collar.

Figure 3. One of the automatic chambers used for measurements of CO_2 and CH_4 fluxes from the forest floor (Papers I and III). Here, measurements of CH_4 exchange at a clear-cut and soil scarified plot in 2010. Photo by Patrik Vestin.

In the CH_4 exchange study (Paper I), four (thinned stand) or five soil chambers were used. Measurements were carried out in the thinned area during 1 August 2009 to 31 May 2010, in undisturbed forest during 7 July to 4 October 2010, at the stump harvested plot during 7 October to 20 October 2010 and at the clear-cut plot during 21 October to 9 November 2010 (Figure 2). The undisturbed forest stand (110-120 years) was adjacent to the thinned stand and had not been subjected to any management in several decades.

In the thinning study (Paper III), it was possible to continue with measurements on three of the collars used before the thinning took place due to wet conditions following thinning (i.e., three of the previously used collars ended up being submerged in small ponds). The collars in the thinned stand were located approximately 100 m SSW of the main tower (Figure 2).

Eddy-covariance measurements

The eddy-covariance (EC) technique was used for measurements of the net exchange of CO_2 between the forest and the atmosphere at the stand level (Paper III). In addition, it was also used for below-canopy measurements of CO_2 fluxes from the forest floor. Both systems consisted of a closed-path gas analyzer (LI-7000, LI-COR Inc., NE, USA) and a sonic anemometer (USA-1, Metek GmbH, Germany). Both gas analyzers were regularly calibrated. For measurements of NEE at the stand level, the flux system was located at 33.5 m height in the main tower (Figure 4), mounted on a boom extending 5 m from the tower. The EC measurements were performed continuously during the period 2007-2016 at a sampling rate of 10 Hz

Figure 4. The 102 m tall flux tower at the ICOS Sweden Norunda station (http://www.icos-sweden.se/station_norunda.html). Photo by Irene Lehner.

The below-canopy flux system was located at 1.5 m height approx. 70 m southwest of the main tower, in the same area as the chamber measurements were performed (Figure 2). Measurements were only performed during the growing seasons 2008-2010.

The EC fluxes of CO_2 and energy were calculated with the EddyPro software, version 6.2.0 (LI-COR, NE, USA), following standard EC methodology. Turbulent fluctuations of the time series data were extracted for half-hourly periods using block averaging. Raw data were screened according to Vickers and Mahrt (1997). The sonic anemometer data were corrected for cross-wind and aligned to the local wind field using double rotation. Gas analyzer data were corrected for fluctuations of water vapor density. Spectral corrections according to Moncrieff *et al.* (1997) were applied. Gap-filling of the CO_2 time series data and partitioning of NEE into ecosystem respiration (R_{eco}) and gross primary productivity (GPP) were done based on Reichstein *et al.* (2005).

Flux-gradient measurements

At the center of all four experimental plots (CW: wet clear-cut, CD: dry clear-cut, SHW: wet stump harvested, SHD: dry stump harvested) at the clear-cut site, 3 m tall towers were erected and equipped for measurements of turbulence parameters and concentrations of CO_2, CH_4, H_2O and N_2O for the period May 2010-May 2013 (Figure 5). Due to instrumental problems with the original N_2O gas analyzer, N_2O measurements were only performed from June 2011 to September 2012.

Wind and turbulence were measured at 2.5 m height (Gill Windmaster, Gill Instruments Ltd., UK) at a rate of 20 Hz. Two air intakes were installed, one at 0.6 m and the second at 2.0 m height, in each tower but were later adjusted to compensate for the increasing height of the vegetation. Air was continuously pulled from each intake to a manifold in the instrument shed located at the center of the clear-cut. Each tower was sampled for 15 minutes per hour. During these 15 minutes, each level was sampled for 150 s before switching to the next level and thus, each level was sampled three times. The air stream from each intake was analyzed for CO_2, CH_4 and H_2O (DLT-100, Los Gatos Research, CA, USA) and N_2O and H_2O (QCL Mini Monitor, Aerodyne Research Inc., MA, USA) at a rate of 1 Hz. In this way, average concentration gradients could be calculated once per hour and plot. These gradients were assumed to be representative for the whole hour. All gas concentrations were corrected for water vapor density fluctuations and in addition, CH_4 and N_2O concentrations were corrected for CO_2 density fluctuations.

Figure 5. One of the three m tall masts equipped for flux-gradient measurements of CO_2, CH_4 and N_2O. The sonic anemometer was mounted at 2.5 m height and the air intakes were at 0.6 m and 2.0 m but were adjusted for increasing height of the vegetation. Photo by Patrik Vestin.

Sensible heat fluxes and other parameters needed for estimating GHG fluxes with the integrated EC and gradient method (flux-gradient) were calculated using the EddyPro software, version 5.0 (LI-COR, NE, USA) for 15-minute intervals corresponding to the gas concentration measurements. Block averaging was used for extracting turbulent fluctuations from the raw data. Raw data were screened using statistical tests (Vickers and Mahrt, 1997). The sonic anemometer data were corrected for crosswind, angle of attack effects (Nakai and Shimoyama, 2012) and was aligned to the local wind field using double rotation. Spectral corrections were also applied (Moncrieff *et al.*, 1997; Moncrieff *et al.*, 2004). Ogive tests (e.g. Desjardins *et al.*, 1989; Oncley *et al.*, 1996) confirmed that averaging intervals of 15 minutes were sufficiently long to capture low-frequency contributions to the fluxes at all plots.

The flux-gradient method is based on Monin-Obukhov similarity theory. Vertical turbulent fluxes F_x of GHGs can be calculated as the product of the vertical concentration of gas x times its turbulent diffusivity (derived from the EC measurements of sensible heat fluxes) as:

$$F_x = -K_x \frac{\partial C_x}{\partial z} \qquad \text{(eq. 1)}$$

where K_x ($m^2\,s^{-1}$) is the turbulent diffusivity of gas x, C_x (µmol mol^{-3}) is the concentration of gas x and z (m) is the measurement height. Since gradients were not determined in a point but over a finite distance, eq. 1 has to be integrated between the air sampling heights z_1 (lower) and z_2 (upper), where z_1 and z_2 are adjusted for the zero-displacement height d.

Thus, F_x can be expressed as:

$$F_x = -\frac{\kappa\, u_*(C_{x,z_2} - C_{x,z_1})}{\ln\left(\frac{z_2-d}{z_1-d}\right) - \Psi(\varsigma)_{z_2} + \Psi(\varsigma)_{z_1}} \qquad \text{(eq. 2)}$$

where κ is the von Kármán constant (set to 0.40, following Högström (1988)), u* is the friction velocity, ψ(ς) is the integrated form of the universal function for sensible heat (Högström, 1988) and ς is a dimensionless stability parameter derived from the EC measurements. The zero-displacement height *d* and roughness length z_0 (a surface property needed for estimations of the source area (footprint) for the GHG fluxes) were estimated from detailed wind profile measurements during 2012. The values of *d* and z_0 were assumed to be valid for the whole measurement period 2010-2013 but were adjusted depending on thickness of the snow cover during wintertime.

A two-dimensional model for calculations of flux footprints (Kljun *et al.*, 2015) were used in combination with a land cover classification map (derived from field surveys and an airborne LiDAR survey in 2011), which made it possible to estimate hourly GHG fluxes (% per m^2) from six land cover classes (classes 1-4: plots CW, CD, SHW and SHD, respectively); class 5: clear-cut and soil scarified area surrounding the experimental plots; class 6: harvested and soil scarified area where seed trees remained until 2012) (Figure 6). By accumulating hourly footprints for the whole measurement period, it was shown that fluxes measured at a specific experimental plot matched the land cover classification of that plot when contributions up to 80% were considered (Figure 6).

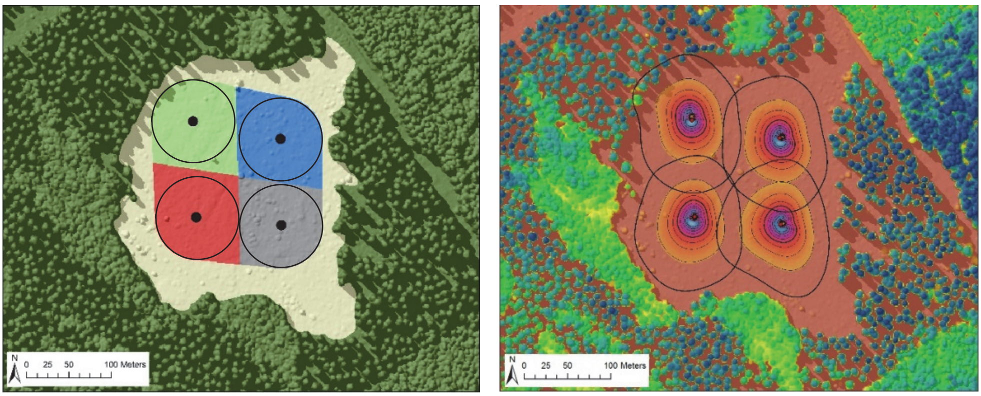

Figure 6. (left) A schematic overview of the experimental plots and land cover classifications: grey, red, blue and green fields represent plots CW, CD, SHW and SHD, respectively; yellow field represents class 5 and dark green field represents class 6.
(right) The hourly foorptints accumulated for a whole year (2012) are shown. Each contour line represent 10% contribution to the accumulated flux footprint, up to 90% contribution. Since there were significant overlap of the 90% contour lines, only contributions up to 80% were considered in Paper II and Paper IV.

Results and Discussion

Clear-cutting and soil scarification (Papers I and II)

Chamber measurements in the mature, undisturbed forest nearby (Figure 2) indicate that the soil in Norunda was a net sink of atmospheric CH_4 in the order of -10 µmol m^{-2} hour^{-1}, while the dry clear-cut plot (CD) was a net source, with average CH_4 emissions of 13.6 µmol m^{-2} hour^{-1}. The chamber measurements at CD showed that four out of five measurement locations were net sources of CH_4, with average emissions up to 32.5 µmol m^{-2} hour^{-1} (Figure 7). Common features at these locations were short distances to the groundwater table (<13 cm) and volumetric soil moisture levels above 40%. This was in good agreement with findings of Castro *et al.* (2000) and Zerva and Mencuccini (2005), who also reported sites to switch from net sinks of CH_4 to net sources following harvest. Three of the net emitting locations at CD also had disturbed soil conditions (mixed organic and mineral soil layers following soil scarification). At these three locations, there were significantly negative correlations between CH_4 fluxes and temperature (i.e., emissions decreased with increasing temperatures), which was surprising since the methanotrophic microbes responsible for CH_4 consumption are expected to have a lower temperature response than the methanogenic bacteria (*Archaeans*) responsible for CH_4 production (Dunfield *et al.*, 1993). These measurements were performed in October-November 2010 when soil temperatures were low and CH_4 production rates could be expected to be low (Dunfield *et al.*, 1993). During periods with precipitation and/or overcast conditions, soil temperatures increased more closer to the surface than at deeper depths, which possibly facilitated CH_4 uptake close to the surface more than it stimulated CH_4 production at deeper soil layers. It is not likely that the negative correlation of CH_4 fluxes to soil temperature at disturbed microsites would remain during periods with higher temperatures in the whole soil profile.

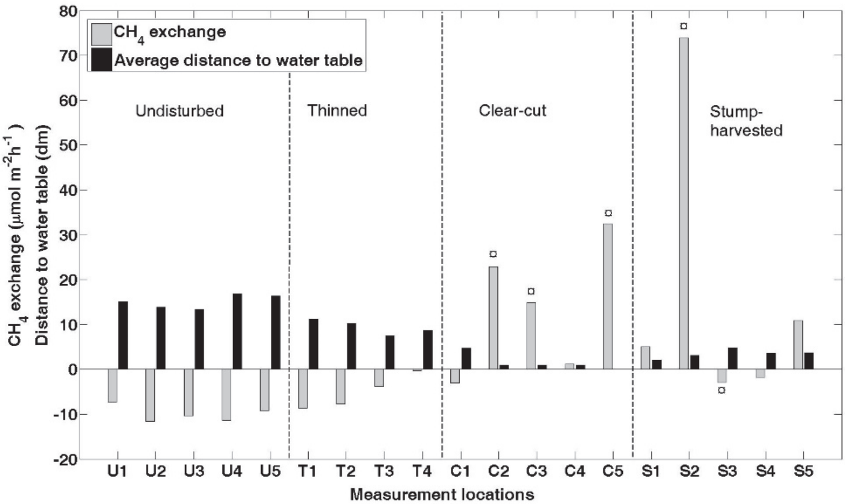

Figure 7. Fluxes of CH_4 (grey bars) from the forest floor measured with the automated chamber system in 2009-2010. The black bars represent the average distance from the soil surface to the groundwater table. The squares above the grey bars marks measurements at disturbed soil.

The flux-gradient measurements integrated fluxes over larger spatial scales than chambers did and therefore included contributions from a wide range of surface conditions in the hourly flux estimates. Due to the extreme heterogeneity of the soil surface at both the wet plot (CW) and the dry plot (CD), it was not possible to find relationships between typical controlling variables (e.g. soil temperature, soil moisture, distance to the groundwater table etc.) and fluxes of CO_2, CH_4 or N_2O.

The clear-cutting resulted in significant emissions of CO_2, CH_4 and N_2O at both CW and CD. Average distances to the groundwater table were 0.16 m and 0.40 m at CW and CD, respectively. The degree of wetness had an impact on the relative contributions of the different GHGs, both directly through the effect of groundwater table position on GHG fluxes, and indirectly through its impact on vegetation development. Vegetation development was faster and more substantial at the wet plot, which resulted in significantly ($p<0.001$) lower net emissions of CO_2 than at the dry plot. At the same time, the wetter conditions resulted in significantly ($p<0.001$) higher CH_4 emissions and significantly ($p<0.001$) lower N_2O emissions than at the dry clear-cut plot.

Average CO_2 fluxes during 2010-2013 were 0.5 µmol m^{-2} s^{-1} and 1.1 µmol m^{-2} s^{-1} at the wet (CW) and the dry (CD) plot, respectively. Respiration dominated at both plots but daily average net uptake during the growing season was visible at CD already in 2010 (Figure 8a). Average CH_4 fluxes during 2010-2013 were 22.6 and 8.2 µmol m^{-2} $hour^{-1}$ at the CW and CD, respectively. While CH_4 emissions were relatively low and stable at the dry plot, they were high and variable at the wet plot, with several emission peaks correlated with precipitation events and/or raised groundwater levels (Figure 8b). Average N_2O emissions during June 2011 to September 2012 were 37.4 µg m^{-2} hour^{-1} and 57.5 µg m^{-2} hour^{-1} at CW and CD, respectively. At CW, N_2O fluxes were highly variable, ranging from large emission peaks to periods with a small net uptake of N_2O (Figure 8c). The emission peaks coincided with precipitation events and freeze/thaw events while periods with net uptake coincided with high groundwater table positions. At CD, fluxes were in general higher but less variable.

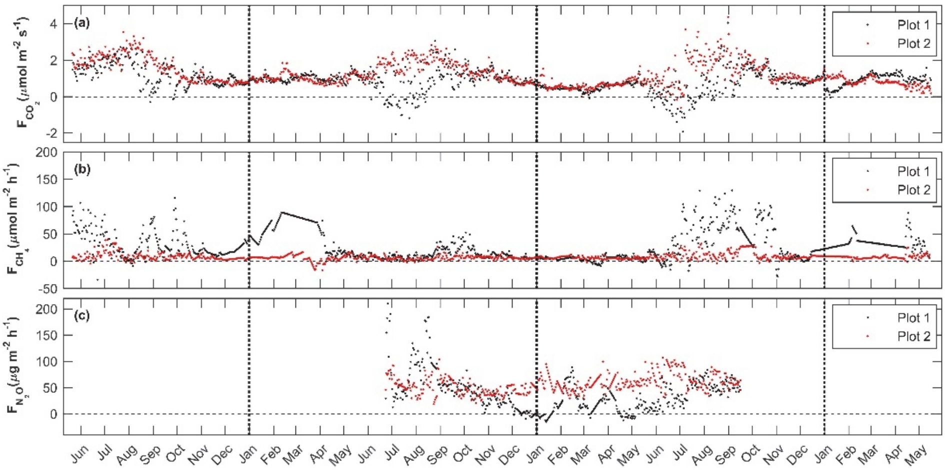

Figure 8. Daily average fluxes of CO_2 (a) and CH_4 (b) from May 2010 to May 2013 and daily average fluxes of N_2O (c) from June 2011 to September 2012. Black dots represent the wet clear-cut plot (CW) and red dots represent the dry clear-cut plot (CD). Vertical dashed lines mark the start of a new year.

A combined GHG budget, including the three main greenhouse gases CO_2, CH_4 and N_2O, was estimated for the period 1 July 2011 to 30 June 2012. Cumulative GHG fluxes were 1070 g m^{-2} of CO_2-equivalents and 1696 g m^{-2} of CO_2-equivalents at the wet (CW) and dry (CD) plots, respectively. CH_4 and N_2O contributed 3.7% and 7.3% respectively at CW and 1.5% and 7.6%, respectively at CD. Thus, N_2O contributed more to the GHG budget than CH_4 did, even at the wet plot that exhibited relatively long periods of net N_2O uptake. The combined carbon budgets (CO_2+CH_4) during 2010-2013 were 4107 g m^{-2} of CO_2-equivalents and 5274 g m^{-2} of CO_2-equivalents at CW and CD, respectively, with CO_2 contributing 91.8% and 98.2%. Cumulative CO_2 fluxes for the whole period were 3773 g m^{-2} of CO_2 and 5181 g m^{-2} of CO_2 at CW and CD, respectively. Ecosystem respiration were similar at both plots and the lower cumulative CO_2 emissions at the wet plot could be fully explained by higher photosynthetic uptake of CO_2 (i.e., higher absolute values of GPP).

The results from both the chamber study (Paper I) and the flux-gradient study (Paper II) indicated that the clear-cutting resulted in waterlogged conditions, which caused the site to switch from a net sink of atmospheric CH_4 to a net source. Vegetation development had a major impact on the combined GHG emissions due to the dominant role of CO_2. N_2O contributed more to the GHG budget at both plots than CH_4 did. The periods with net N_2O uptake was probably a consequence of increased reduction of N_2O to N_2 by denitrifying bacteria during periods with superficial groundwater.

The results from Papers I and II highlight the importance of considering the combined effect of forest management on fluxes of CO_2, CH_4 and N_2O when evaluating the climate mitigation potential of different forest management policies or silvicultural systems. While the flux-gradient system proved well-suited for inter-plot comparisons at a soil scarified clear-cut, it is clear that future studies should better account for the extreme spatial variability in soil surface conditions and related variabilities in soil temperature, soil moisture, soil properties etc. Ideally, long-term measurements that integrate fluxes spatially and temporally should be combined with continuous automatic soil chamber measurements as well as manual chamber measurements to gain better understanding of the drivers of GHG fluxes at heavily disturbed clear-cuts. Furthermore, such long-term measurements should be made using standardized methods in representative forest ecosystem (in terms of species, site productivity, soil properties, climate etc.) and should be combined with modeling efforts to be able to draw generalizing conclusions.

Thinning/selective cutting (Papers I and III)

After thinning in November 2008, soils got wetter and the groundwater table was raised and remained, on average, higher for about two years. At many places within the thinned sector (Figure 2), soils were waterlogged and large ponds of water were formed. Three of the six collars used for soil respiration measurements before the thinning ended up below the water surface and could not be used for post-thinning measurements. The remaining three collars were located slightly higher in the terrain.

The automated chamber measurements of CO_2 fluxes in 2008 and 2009 showed that soil respiration increased considerably following thinning and that the temperature sensitivity of soil respiration had increased. The nighttime CO_2 fluxes were 150% to 240% of the pre-thinning values at an air temperature of 10°C and 160% to 275% at 20°C. The below-canopy EC measurements also indicated increased nighttime CO_2 emissions from the forest floor during May to September, but the effect was much less pronounced than suggested by the chamber measurements. The first two years after thinning, emissions were 29% and 15% higher, respectively, than pre-thinning emissions. Considering the increased input of aboveground litter (harvest residues) and of root litter following thinning, increased CO_2 emissions from the forest floor were in line with our expectations and in good agreement with other studies (e.g. Sullivan *et al.*, 2008). It is likely that the stronger response seen in the chamber measurement was a result of measurements at slightly elevated positions where soil respiration was not limited by anaerobic conditions caused by the raised groundwater table. The EC measurements integrated fluxes over a larger area and its footprint included both waterlogged and drier areas and thus, are likely to be more representative for the response of soil respiration to thinning in this area. Daytime below-canopy fluxes were less enhanced than nighttime fluxes, which indicates a compensatory effect by ground vegetation following thinning, as reported by e.g. Vesala *et al.* (2005) and/or decreased belowground autotrophic respiration.

The automated chamber measurements of CH_4 fluxes in 2009 and 2010 showed that the thinned stand remained a net sink of atmospheric CH_4, although the sink strength was reduced compared to the adjacent undisturbed forest (Figure 2). Average CH_4 uptake was -5 µmol m^{-2} $hour^{-1}$ and -10 µmol m^{-2} $hour^{-1}$ in the thinned and undisturbed stands respectively. In both stands, there were significant correlations between CH_4 uptake and soil temperature, soil moisture and groundwater table position at all measurement locations, although the response to changes in drivers varied between locations and over time. Dannenmann *et al.* (2007) found no effect of thinning of a temperate deciduous forest on CH_4 exchange 4-6 years after thinning at one site, and reduced CH_4 uptake after one year at a second site. Others have reported no effect on CH_4 consumption following thinning of a coniferous forest, either in the short-term (one year) (Sullivan *et al.*, 2008) or long-term (ten years) (Wu *et al.*, 2011).

The above-canopy EC measurement were performed for two years before the thinning and for eight years after the thinning. The daytime uptake decreased by approximately 30% the first growing season after thinning. At the same time, there was a small reduction in total ecosystem respiration, despite the enhanced CO_2 fluxes from the soil. The net effect was lower net CO_2 uptake during growing seasons. This was in good agreement with findings by Scott *et al.* (2004). During the following years, there was a decreasing trend in nighttime ecosystem respiration and an increasing trend in daytime CO_2 uptake during growing seasons, while there were no trends in modeled respiration (following Lloyd and Taylor, 1994) or daytime NEE (following Michaelis and Menten, 1913). This indicate that the observed trends were a result of the thinning and not because of trends in drivers.

Following thinning in 2008, the annual gap-filled NEE was more positive in 2009 and in 2011 (Figure 9) but were close to, or lower than, pre-thinning levels all other years. Both GPP and ecosystem respiration were lower after thinning but since the reductions were of similar magnitude, NEE remained relatively stable. This was in good agreement with other studies from different forest ecosystems and with different thinning strengths (Vesala *et al.*, 2005; Granier *et al.*, 2008; Saunders *et al.*, 2012; Wilkinson *et al.*, 2016).

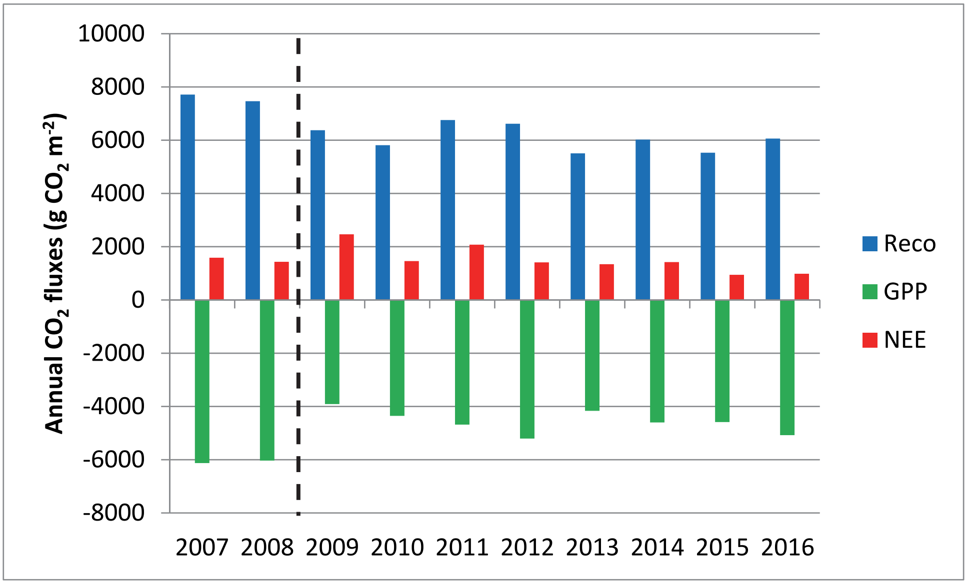

Figure 9. Annual values of net ecosystem exchange (NEE: red bars), ecosystem respiration (R_{eco}: blue bars) and gross primary productivity (GPP: green bars) for the period 2007-2016. The vertical dashed line marks when thinning was performed.

The contrasting results on NEE between growing seasons and whole years can probably be explained by the reduced ecosystem respiration, since this has an effect on NEE all year round. There were also indications that increased CO_2 uptake by ground vegetation following thinning contributed to the observed minor effect on NEE.

The combined results of Papers I and III are an indication that a selective cutting system could maintain a constant NEE over time, without major negative effects on soil CH_4 uptake of forest soils. It seems possible that such system could enhance the mean CO_2 uptake of forests stands as compared to even-aged forestry and hence, enhance the climate mitigation potential of forests. However, more studies in uneven-aged forests are needed and should include studies of productivity, effects on soil carbon stocks, nutrient leaching, effects on biodiversity etc. in order to better assess if a selective cutting system could be a sustainable silvicultural system.

Stump harvesting (Papers I, II and IV)

The automated chamber measurements of CH_4 fluxes at the dry stump harvested and soil scarified plot (SHD) in 2010 revealed that the plot was a net source of CH_4 of similar magnitude as the dry clear-cut plot CD (average emissions of 17.0 µmol m^{-2} hour^{-1} and 13.6 µmol m^{-2} hour^{-1}, respectively), but the variation between different measurement locations were larger, ranging from -2.9 to 74.0 µmol m^{-2} hour^{-1} (Figure 7). Both the highest net uptake and the highest net emissions were from disturbed soils. The net uptake of CH_4 at the disturbed location was probably because the chamber collar was placed on top of a mound created during additional soil scarification and had a relatively large distance to the groundwater table (Figure 7). Also Strömgren *et al.* (2016) noted small differences in average CH_4 fluxes between soil scarified and stump harvested clear-cuts, but in contrast, they only noted net emissions from soil pits where stumps had been extracted and from wet wheel-ruts and found low net consumption of CH_4 at other types of disturbed soil.

As in the case with clear-cutting and soil scarification (Paper II), there were substantial net emissions of CO_2, CH_4 and N_2O following stump harvesting and soil scarification according to the flux-gradient measurements Within the same treatment, the degree of wetness caused significant differences in fluxes of CO_2, CH_4 and N_2O between the dry and the wet plots. Significant treatment effects on CO_2 and N_2O fluxes were found at the dry plots (CD and SHD). Average CO_2 fluxes during May 2010-May 2013 were 0.7 µmol m^{-2} s^{-1} and 0.9 µmol m^{-2} s^{-1} at the wet (SHW) and dry (SHD) plots, respectively. Average CH_4 fluxes during the same period were 16.8 µmol m^{-2} hour^{-1} and 6.6 µmol m^{-2} hour^{-1} at SHW and SHD, respectively. Average N_2O emissions during June 2011 and September 2012 were 20.6 µg m^{-2} hour^{-1} (SHW) and 101.0 µg m^{-2} hour^{-1} (SHD).

For the measurement year 1 July 2011 to 30 June 2012, the combined GHG budgets, expressed in grams of CO_2 equivalents per square meter (using GWP_{100} factors) were 1224 and 1442 g m^{-2} of CO_2-equivalents at SHW and SHD, respectively (Table 1) and, for comparison, 1070 and 1696 g m^{-2} of CO_2-equivalents at the wet (CW) and dry (CD) clear-cut plots, respectively. The GHG budgets at the stump harvested plots were dominated by CO_2 fluxes while CH_4 contributed 3.3% and 1.4% at SHW and SHD, respectively and N_2O contributed 3.2% and 17.0%.

For the whole period 2010-2013, the cumulative NEE was ~1160 g m^{-2} of CO_2 lower at the dry stump harvested plot (SHD) than at the dry clear-cut plot (CD). The estimated respiration from the stumps at plot 4 (if they had been left in the soil) was ~1280 g m^{-2} of CO_2, and thus, this suggests an indirect effect (increased soil respiration after stump harvesting) in the order of ~120 g m^{-2} of CO_2.

Considering the uncertainties in flux measurements, estimations of stump biomass, stump decomposition and harvested surface area, it is not possible to determine whether or not this is a significant effect. However, it is an indication of reduced climate mitigation potential of using stumps for bioenergy production and is in good agreement with findings of Grelle *et al.* (2012). At the wet plots, cumulative NEE was ~330 g m^{-2} of CO_2 higher at the stump harvested plot, which indicates an indirect effect of ~1610 g m^{-2} of CO_2 after three years. However, differences in wetness and vegetation cover and distribution between these plots makes it difficult to draw robust conclusions and these results should be interpreted cautiously.

Carbon fluxes and pools are highly dynamic over time and three years of measurements of GHG fluxes are not sufficient to account for the net effect of stump harvesting on soil carbon pools and on the climate system. Preferably, the effects should be studied over one, or several rotation periods. Short to medium term (8-39 years) studies on soil carbon pools after stump harvesting revealed no, or only small effects, as compared to even-aged forestry (clear-cutting and soil scarification) (Karlsson and Tamminen, 2013; Strömgren *et al.*, 2013; Hyvönen *et al.*, 2016; Jurevics *et al.*, 2016; Persson *et al.*, 2017). This is an indication that stump harvesting does not lead to any significant indirect effects. It is also possible that indirect effects on soil respiration following stump harvesting might be cancelled out due to increased growth (of trees and ground vegetation) over time. Egnell (2016) reported effects of harvest intensity on forest production but the response depended on intensity, species and site productivity. In general, increased harvest intensity had positive effects on production in pine but negative effects on spruce when stumps and slash were removed (Egnell, 2011). The study did not include effects on ground vegetation or soil carbon.

Table 1.

Cumulative GHG gas fluxes for year 1 (May 2010 to May 2011), year 2 (May 2011 to May 2012) and year 3 (May 2012 to May 2013). The GWP_{100} factors used in the conversions of CH_4 and N_2O fluxes into CO_2-eq. were 28 and 265, respectively (Myhre et al., 2013).

* N_2O fluxes were not measured during Year 1. ** Note that the contribution of N_2O to the full GHG budget is based on 11 months of data in year 2 and on only 4 months in year 3. *** Year is here defined as 1 July 2011 to 30 June 2012, to make possible a direct comparison of the importance of the different GHGs. CW: wet clear-cut; CD: dry clear-cut; SHW: wet stump harvested; SHW: dry stump harvested

Plot	**Year**	**NEE** (g m^{-2} of CO_2)	**Reco** (g m^{-2} of CO_2)	**GPP** (g m^{-2} of CO_2)	**CH_4** (g m^{-2} of CO_2-eq.)	**N_2O** (g m^{-2} of CO_2-eq.)	**Sum** (g m^{-2} of CO_2-eq.)
CW	1	1607.9	2287.8	-679.9	153.1	-	1761.0*
CD	1	1911.2	2083.1	-171.9	30.3	-	1941.5*
SHW	1	1499.3	1889.2	-389.9	89.2	-	1588.5*
SHD	1	1671.4	1750.4	-79.0	28.3	-	1699.7*
CW	2	1052.5	2507.8	-1455.3	37.6	78.2	1168.3**
CD	2	1645.0	2152.8	-507.8	25.3	111.9	1782.2**
SHW	2	1271.0	2189.3	-918.4	36.1	39.8	1346.9**
SHD	2	1378.6	1734.2	-355.6	19.9	220.3	1618.8**
CW	3	1112.7	2589.7	-1477.0	143.1	32.5	1288.3**
CD	3	1624.7	2556.3	-931.6	37.9	52.2	1714.8**
SHW	3	1330.4	2515.3	-1184.9	74.6	18.4	1423.4**
SHD	3	972.5	1907.8	-935.4	43.6	73.0	1089.0**
CW	1-3	3773.1	7385.3	-3612.1	333.8	110.7	4217.6**
CD	1-3	5180.8	6792.1	-1611.3	93.5	164.1	5438.4**
SHW	1-3	4100.7	6593.8	-2493.1	199.8	58.2	4358.8**
SHD	1-3	4022.5	5392.4	-1370.0	91.8	293.2	4407.4**
CW	***	952.7	2456.5	-1503.8	39.3	77.9	1069.9
CD	***	1541.0	2174.8	-633.8	25.8	128.8	1695.7
SHW	***	1144.1	2188.4	-1044.3	39.6	39.9	1223.6
SHD	***	1176.0	1743.6	-567.6	20.6	245.7	1442.4

When considered together with previously reported effects of stump harvesting on the climate and the environment, the results of Papers I and IV suggests there might be a potential for using stumps for bioenergy production in Sweden. However, the mitigation potential might be reduced due to possible indirect effects on soil respiration following stump harvest. Uncertainties remain regarding the importance of soil wetness and its impact on vegetation development and related impacts on fluxes of CO_2, CH_4 and N_2O. The high N_2O emissions at the dry stump harvested plot (SHD) is a cause for concern and an indication that the mitigation potential of stumps is further reduced. Thus, there is a need for more spatially and temporally integrating measurements of N_2O fluxes at stump harvested clear-cuts with different soil properties, site productivity etc. Considering that biomass harvesting is proposed as a means to reduce Sweden's climate impacts in the short term (a few decades), it might be more realistic to use GWP_{20} factors when quantifying the contributions from CH_4 and N_2O. This would triple contributions from CH_4 and further reduce the mitigation potential of using tree stumps for bioenergy production.

Summary, conclusions and outlook

Flux-gradient measurements of CO_2, CH_4 and N_2O using only one set of gas analyzers proved to be a reasonable compromise between cost (in terms of instruments, maintenance and running costs), data coverage and accuracy. The system proved well suited for robust inter-plot comparisons and allowed for spatial replications of experimental plots. This proved to be very important considering the different degrees of wetness and vegetation development at the different plots. Even if stump harvesting is not expected to take place at wet soils, it is not always possible to determine how clear-cutting will affect the hydrology of a forest stand. Our clear-cut stand was classified as mesic by the forest owner and still turned out to be quite wet following clear-cutting. This emphasizes the importance of spatial replication of flux towers when trying to generalize findings to the ecosystem level.

Forest management had clear effects on the soil CH_4 exchange. Reduced evapotranspiration following harvest (thinning and clear-cutting) resulted in increased soil moisture and in a raised groundwater level, which reduced CH_4 uptake in the thinned stand and caused the whole clear-cut stand to switch from a net sink to a net source of CH_4. This finding (Paper I) was supported by the long-term flux-gradient measurements (Papers II and IV).

Clear-cutting and subsequent soil scarification (mounding) resulted in substantial emissions of CO_2 at both the wet (CW) and dry (CD) plots. The degree of wetness had significant effects on vegetation development and on GHG fluxes. Lower net emissions of CO_2 at the wet plot was partially offset by higher CH_4 emissions. N_2O contributed more to the total GHG budgets at both plots than CH_4 did (in a 100-year perspective) (Paper II).

Stump harvesting and soil scarification (mounding) had a significant effect, as compared to control plot, on CO_2 and N_2O fluxes at the dry plots, while no treatment effect was found at the wet plots. Total CO_2 emissions were lower at the dry stump harvested plot than at the control plot but there were indications of an indirect effect, i.e., of 'extra' CO_2 emissions of 120 g m^{-2} of CO_2 from the soil during 2010-2013. Although this effect is within the uncertainties of the measurements, it is an indication of reduced climate mitigation potential of tree stumps. In addition, the high N_2O emissions at the dry plot point towards further reduced mitigation potential. Measurements at the wet plots indicated a significant indirect effect at the wet stump harvested plot, which suggests a negative mitigation potential (in other words, the 'extra' CO_2 emissions from the soil were larger than the avoided emissions from the stumps). However, these results should be treated with caution since there were differences in wetness and vegetation development and vegetation cover between these plots that were not properly accounted for (Paper IV).

The simulated selective cutting (thinning from below) resulted in increased emissions of CO_2 from the forest floor the first years after thinning. At the same time, daytime CO_2 uptake and ecosystem respiration decreased during the main growing seasons (May-September), with the net effect being a reduced CO_2 uptake at the stand level. This effect was long-lasting and growing-season NEE had not fully recovered eight years after thinning. In contrast, on an annual basis, the reduced ecosystem respiration had a larger impact on NEE than the reduced growing season uptake, which eliminated the negative impact on the annual NEE. Increased CO_2 uptake by ground vegetation after thinning might explain a part of why only a minor effect was observed on the whole ecosystem NEE (Paper III).

Taken together, the studies presented in this thesis underscore the importance of accounting for all greenhouse gases when considering short-term effects of forest managements on the climate system. Combined, Papers I-IV, indicate that any forest management system that avoids substantial net emissions of GHGs during a clear-cut phase and maintains a high CO_2 uptake and a large standing volume might have a stronger mitigation potential than conventional even-aged forestry. However, it should be pointed out that short-term studies of possible climate benefits of using a selective cutting system that maintains a forest cover and constant NEE is not the same thing as saying that this is a complete alternative to existing silvicultural systems. Rather, it is an indication that there might exist alternatives that maintain a high productivity and also have positive impacts on ecosystem services, on biodiversity and on the climate system.

The continuous multi-plot GHG measurements at a clear-cut boreal forest site reported here are, to my knowledge, the first of its kind. There is a clear need of continued long-term measurements of GHGs in forests with different conditions (management, species, soils, climate etc.) to unravel the full effect of forest management on the climate. Such measurements should be combined with investigations aiming at quantifying nitrogen leaching and biophysical effects (changes in albedo and surface energy fluxes) and modeling efforts. In addition, changes in soil carbon and nutrient pools, how harvested wood is used and substitution effects of using bioenergy from forest need to be included in a full assessment of the net effects on the climate. It is especially important with new studies in uneven-aged forest stands managed through selective cutting to increase our understanding of how forests can be managed in a sustainable way, with enhanced climate mitigation potential without negative environmental and socio-economic consequences.

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