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Spatiotemporal variation of carbon stocks and fluxes at a clear-cut area in central Sweden

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Abstract

Forests have a large role in the global carbon cycle. Forest management could play a crucial role in mitigating climate change. With a growing demand for renewable energy the forest could contribute. Stumps are one of the potential energy sources from the forest. In this study a pine dominated clear-cut area was surveyed in regard of stump biomass, carbon fluxes and carbon (C) and nitrogen (N) stocks. Stumps were positioned and measured, and the remaining biomass on the site was calculated. With a mobile soil respiration system soil respiration measurements were conducted. The area held a biomass of 50.3 ton/ha, representing 18% of pre-harvest forest biomass. The clear-cut area held large stocks of both carbon and nitrogen, 14 kg C/m^2 and 0.48 kg N/m^2 respectively. The mean soil respiration rate was 2.48 μmol m^{-2} s^{-1}, which is consistent with both eddy covariance measurements and similar earlier studies at the site. Soil respiration rates in relation to soil temperature, disturbance and C and N stocks were examined but no distinct correlation could be found.

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Variationer i kollager och kolflöden på ett kalhygge i centrala Sverige

Populärvetenskaplig sammanfattning

Av jordens yta är ca 30 % täckt av skog och mer än 80 % av allt kol inbundet ovan mark återfinns i skogens växtlighet. Skogen är kopplad till atmosfären genomflöden av bland annat energi, vatten och koldioxid. Hur skogen brukas kan därför påverka klimatförändringen. När skog avverkas tas det mesta av det inbundna kolet ovan mark bort. Kvar är resterna från avverkningen redo att brytas ner.

Skogen är idag en energikälla som anses förnybar. Med ett samhälle som satsar på förnyelsebar energi kommer skogsbruket utvecklas. Stubbar är en ny komponent i skogsbruket och som potentiellt kan fungera som bränsle. I denna studie undersöktes ett kallhygge som i framtiden skall stubbskördas. Hygget kommer efter stubbskörd ingå i ett forskningsprojekt, där man tittar på effekterna av stubbskörden. Denna studie fungerar då som en utgångspunkt att jämföra mot. Undersökningen fokuserade på biomassamängden i stubbarna, kolflöden, och markens kol- och kväveförråd. För att se om någon parameter inverkade på kolflödena undersöktes även marktemperatur, hur mycket marken hade belastats av avverkningen och hur mycket avverkningsrester som låg kvar på marken.

Stubbarna positionerades och mättes för att sedan kunna beräkna rumslig variation och mängden biomassa kvar på området. Jordprover togs för att kunna bestämma kol- och kväveförråden. Med ett mobilt markrespirationssystem mättes koldioxidflöden från marken till atmosfären. Området innehöll 50,3 ton/ha biomassa vilket motsvarade 18% av vad som ursprungligen fanns där. Kol- och kväveförråden i marken var stora, 14 kg C/m^2 respektive 0,48 kg N/m^2. Koldioxidflödet från marken var 2.48 μmol m^{-2} s^{-1}, vilket överensstämmer med liknande mätningar från hygget och med resultat från tidigare studier i området. Samband mellan kolflöden och marktemperatur, störningsgrad och kol- kväveförråd undersöktes men inga tydliga relationer kunde hittas.

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1. Introduction

Forests cover approximately 30% of the Earth's surface and store more than 80% of all terrestrial aboveground carbon (Jóbbagy and Jackson, 2000). Forests interact with the atmosphere through e.g. energy, water and carbon dioxide (CO_2) exchange and in that way influence the climate. Forest management therefore has the potential to mitigate climate change (Bonan, 2008). A common forest management practice in Sweden is clear-cutting where all trees are removed at ground level, leaving stumps, foliage and branches on the site. Regarding the carbon cycle, this measure eliminates almost all photosynthesis and autotrophic respiration (Kowalski *et al.*, 2004). Left is bare ground and logging residues ready to decompose. The storage of soil carbon is controlled by the balance of inputs – photosynthesis and dead organic matter, and the outputs – heterotrophic respiration and belowground autotrophic respiration (Schlesinger, 1977). Decomposition is controlled by many factors, such as substrate availability, soil temperature, soil moisture and oxygen supply amongst other. Boreal forests have low decomposition rates and accumulate therefore more carbon in the soil as compared to other forested biomes.

With energy transition towards more renewable energy, the demand for forest fuel is expected to grow. Recently, harvesting stumps for energy purposes has become interesting (Näslund Eriksson & Gustavsson, 2008). The Swedish Forest Agency (2009) estimates a restricted area of Swedish clear-cuts to be used for stump harvest and proposes this industry to add 1.3-2.6 TW/yr to the yearly energy production.

Objectives

One of the purposes of this study was to contribute with a detailed survey of a clear-cut area that is used as study site for extensive research on the effects of stump harvesting on greenhouse gas exchange, nitrogen leaching to the ground water and the consequences for the water balance. The stump harvest did not take place during this study. This study aims only to contribute with reference data, in terms of carbon and nitrogen stocks, carbon dioxide fluxes and biomass distribution. This gives extensive knowledge of the area before the harvest. The objectives are to answer the following questions:

- How much biomass does the clear-cut site contain in terms of stumps?
- How large are the CO_2 emissions from a clear-cut area and what factors affect the emissions?
- How do the emissions vary over time and over the site?
- How large are the carbon and nitrogen stocks and do they affect the CO_2 emissions?
- Do disturbances from the clear-cutting affect the CO_2 emissions?

2. Theoretical Background

2.1 Carbon storage in forests

The annual gross uptake of carbon between forests and the atmosphere is ~59 Pg C/yr (Beer *et al*., 2010), which is about 7 times the anthropogenic carbon emissions. However, the respiration is only slightly smaller resulting in a net uptake of 0-6 Pg C/yr for the terrestrial land surface (Le Quéré *et al*., 2009). European forests absorb 7-12% of European anthropogenic emissions, and thus, European forests are currently a sink of CO_2 (Jandl *et al.*, 2007). The management of forests does have a large impact on the carbon dioxide exchange, and the management strategy will therefore have an effect on the development of carbon pools in soil and in above ground vegetation. Climate change could result in changes in both soil respiration and photosynthesis. The result could be increased CO_2 emissions from forest ecosystems but the outcome is difficult to predict (Jandl *et al.*, 2007).

Photosynthesis and respiration

It is through photosynthesis that plants gain energy. With the help of solar radiation, atmospheric CO_2 and water is transformed into oxygen and sugar. The energy is then used to build new biomass and for energy supply (Chapin *et al*., 2002).

In plant respiration, sugar and oxygen are used and transform back into water and CO_2. Plant respiration is also called autotrophic respiration and is divided in aboveground plant respiration and belowground plant respiration (often meaning root respiration). Both plants and microbes respire. Microbial respiration is also called heterotrophic respiration and takes place during decomposition of litter and soil organic matter (SOM) (Luo and Zhou, 2006). Depending on vegetation type and season root respiration varies a great deal (Hanson *et al*., 2000). Early in the growing season root respiration can account for 35-60% of the total respiration. In the end of the growing season the root respiration have decreased to 12-16% of the total respiration (Widén and Majdi, 2001). The roots live in symbiosis with mycorrhiza and supply them with carbon in exchange for nutrients and water. 10-50% of the daily carbon fixed through photosynthesis is lost through root respiration (Luo and Zhou, 2006).

The carbon exchange between forest and atmosphere can vary over both shorter and longer periods, affected by differences in weather and climate. The correlation between incoming solar radiation and photosynthesis is strong for a tree (Chapin *et al*., 2002). Photosynthesis increases strongly with increasing temperature, with a maximum around 15-20°C. During summer photosynthesis is limited by incoming solar radiation and water supply while during winter the limiting factors are temperature and ground frost. Below soil temperatures of 5°C, microbial activities strongly decline. However, measurable respiration has been found down to -39°C (Panikov *et al.*, 2005). With every 10°C increase, respiration more than doubles and reaches a maximum around 35-40°C (Brady & Weil, 2002). Below ground respiration accounts for 30-80% of the total respiration from a forest (Luo and Zhou, 2006). Due to the Swedish climate a larger part of photosynthesis and respiration take place during the six warmest months of the year (Bergh et al., 2000).

Net carbon balance

The growth of a forest is determined by many factors such as age, climate, species structure, silviculture and disturbances. Since the net carbon exchange (NEE) is small compared to the size of photosynthesis and respiration, it is sensitive to environmental and climatic changes. Small changes in these large fluxes can result in that forests are going from being carbon sinks to becoming carbon sources on an annual basis. In general, a forest is a carbon sink during summer and a carbon source during winter (Morén et al., 2000).

In forestry, clear-cutting is a common harvest practice. During this procedure all trees are cut at ground level, leaving foliage, twigs, branches, stumps and root systems on site as residues. Clear-cutting alters the carbon cycle – the photosynthesis and the autotrophic respiration is now removed and the decomposition increases due to higher substrate supplies from the dead roots, twigs and branches. The bare ground gets more sun exposure and that further stimulates the decomposition through higher soil temperatures. Clear-cut stands are rather large carbon sources (Kowalski *et al.*, 2004).

2.2 Soil carbon

Soils contain the largest organic carbon reservoir on Earth. SOM is the organic fraction of the soil. Surface litter is usually not included (Luo and Zhou, 2006). Long-term sequestration of soil organic matter takes place in the top layer of forest soils, the humus layer (Ovington 1957, 1959). Berg *et al.* (2009) suggest that the sequestration rate is dependent on tree species and type of ecosystem. Their study showed that forests dominated (>70%) by Scots pine had a higher C sequestration rate than forests dominated by Norway spruce. The organic part of soils supplies nutrients for plant growth, maintains soil fertility through cation exchange and improves soil structure (Luo and Zhou, 2006).

The inputs of carbon in soils, photosynthesis and dead organic matter, in relation to the outputs, heterotrophic respiration and root respiration, control the storage of soil organic carbon (SOC) (Schlesinger 1977). Carbon stored deeper in the soil have a longer mean residence time (Fontaine *et al.*, 2007).

Fontaine *et al* (2007) suggest that fresh plant-derived carbon stimulate microbial mineralization of old carbon in deeper soil layers. This gives that a decreased fresh carbon input from plants could result in decreased decomposition. If the supply of fresh plant-derived carbon increases this could stimulate old carbon in deep soil layers to decompose and be released (Fontaine *et al.,* 2007).

2.3 Factors affecting soil CO_2 production and transport

Dead organic matter accumulates at the ground surface in the form of litter. The dead biomass is then decomposed and in this process a large amount of CO_2 is released back to the atmosphere. Decomposition is controlled by a number of variables, such as soil moisture, soil texture, oxygen supply, nutrient status and root penetration resistance. Boreal forests produce small amounts of litter, but because of lower decomposition rates (boreal forests are located in colder regions) they accumulate more. Different components of litter have different decomposition rates, and microbes produce distinct enzymes to take care of the various litter groups (Brady & Weil, 2002).

Respiration rates are usually high in the early stages of decomposition, processing the light biodegradable organic matter first. Further on the remaining litter decomposes more slowly. Decomposition is affected by three different processes. Through *leaching* soluble materials, such as sugars, amino acids and organic acids, are transferred away from decomposing organic matter through water transfer into the soil matrix. Then bacteria and "sugar-fungi" rapidly decompose them. The larger parts of litter are broken down by soil animals in *fragmentation* and give material with greater surface area and moisture-holding capacity than the original litter. The *chemical alteration* includes microorganisms with enzymes that initiate the breakdown of compounds and macromolecules that are too insoluble or too big for other microbes to absorb and metabolize (Brady & Weil, 2002).

When the supply of oxygen is satisfactory, organic compounds oxidise to CO_2, water and energy. Many intermediate steps are involved in this overall reaction, and dependent on side reactions involves elements other than carbon and hydrogen.

The soil consists of pores of different sizes, either filled with water or air. Air in soils differs greatly from the atmospheric air, the CO_2 concentration is usually much higher and the oxygen concentration lower. The moisture content of soil air is often higher than atmospheric air. The composition varies from place to place, some gases are consumed by roots or microbes, others are released (Brady & Weil, 2002).

Air-filled pores in the soil allow CO_2 to travel to the surface. Gas exchange between soil and atmosphere takes place through two mechanisms, *mass flow* and *diffusion*. Several factors affect these mechanisms. Temperature and atmospheric pressure changes can cause the air in the soil to expand or contract. Rain water entering the soil can push out old air with high CO_2 concentration. Winds blowing over a surface can push air down, or suck air out of the soil. The water table in the soil can influence the air movement. Both mass flow and diffusion can take place in both soil air and soil water. Mass flow is generally a minor exchange form. The larger part of soil-atmosphere exchange occurs by molecular diffusion in soil air. This transport is driven by the gradient of CO_2 concentration of molecules in the air. CO_2 molecules diffuse from areas with high concentration to low concentration areas (Luo and Zhou, 2006).

2.4 Nitrogen cycle in forest ecosystems

Nitrogen (N) is the third most abundant element in plant dry matter. Only oxygen and carbon are larger components in plants. N is acquired by plants in greater quantity from the soil than any other nutrient. N inputs to an ecosystem occur naturally via biological fixation and by dry and wet deposition and by human force through N fertilizers. N can be transported from ecosystems in liquid, solid and gaseous phases. Gaseous emissions, leaching and offsite transport due to erosion are common transport ways.

Plants can only acquire N from the soil in the form of NH_4^+, NO_3^- or simple organic forms – amino acids. The ions are products of N mineralization in the soil. Plant uptake of N depends on N-ion concentrations in the soil, root distribution with enhanced uptake by mycorrhiza, soil water content and plant growth rate. Once absorbed into the plant, N is converted to amino acids and proteins.

In unmanaged ecosystems most of the N in plants is returned to the soil as litter, or from excreta of grazing animals (McNeill and Unkovich, 2007).

When organisms decompose organic matter, carbon is used as energy, whereas nitrogen is needed for building cell structure. More carbon than nitrogen is needed and therefore the C/N ratio is of interest. Optimal decomposition occurs when C/N ratio is between 20 and 31 (web source [1]).

2.5 Stump harvest

Stump harvest is not a new commodity in Sweden. During the 19th century pine stumps were used to manufacture wood tar. In the 1970's and 80's, stumps provided raw material for the pulp and paper industry. In the clearing-up process after the storm Gudrun in 2005, Swedish forest companies saw an opportunity in harvesting stumps for energy purposes. With energy transition towards more renewable energy and increasing energy prices Swedish forest companies saw a possibility to make stump harvest profitable (Skogsstyrelsen, 2009). By increasing the extraction of slash and stumps an additional 40 TWh could be added without any bigger modifications to today's forestry (Energimyndigheten, 2007). The Swedish Forest Agency (2009) estimates 26 TWh without any bigger modifications and that only a restricted areal, 5-10%, would be used for stump harvest in the near future. That gives a realistic number of 1.3-2.6 TWh/year.

It is important to examine the negative effects stump harvest could have on the affected environment. There are factors such as nutrient loss, soil type vs. erosion, soil moisture and biodiversity to take in to account. The Swedish Forest Agency finds that the possibility to replace fossil fuels with stump harvest will bring positive effects to the climate and that the negative aspects of stump harvest are small in comparison to what could be gained. The Swedish Forest Agency recommends

- that earlier precautions for site specific forestry management are maintained and that only well-conditioned grounds are harvested
- that enough stumps are left on site to maintain a high biodiversity
- that the risk of soil compaction and soil damage and subsequent erosion are minimized
- that pollution of nearby aquatic environments is avoided
- that acidification of soil or water will not occur and avoidance of disturbing the soil nutrient balance
- that damage to cultural sites are avoided and that the conditions for recreation and reindeer husbandry do not deteriorate to any great extent

3. Materials and Methods

3.1 Site and stand

The studied clear-cut area was situated in Norunda, *ca.* 30 km north of Uppsala (60°5´N, 17°29´E, 45 m a.s.l.). In Uppsala, the mean annual temperature is 5.5 °C (1961-1990) and the mean annual precipitation 527 mm (Lundin *et al*., 1999). The harvest took place during early spring 2009. Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) dominated the area before cutting, but common birch (*Betula pubescens*) was also present. The soils are sandyloamy tills and contain high amounts of stones (Lundin *et al.*, 1999). The Norunda forest is annually a carbon source (Lindroth *et al*., 1998).

3.2 Design of field study

The clear-cut area was divided in four equally sized plots (fig. 3.1), each with a diameter of *ca*. 100 m giving the studied site a size of 3 ha in total. In between the four plots was a gas analyzer shed. In the middle of each plot was a tower measuring CO_2, CH_4, H_2O and N_2O concentrations at two different levels. Two of the towers also measured CO_2 and H_2O exchange through the so-called Eddy Covariance (EC) technique. During this field study the plan was that plots 2 and 4 should undergo stump harvest, but in reality, due to the diverse soil moisture, plots 3 and 4 were harvested instead, leaving plots 1 and 2 as references. Each plot was assigned 9 measuring points where measurements of soil respiration, carbon and nitrogen stocks and harvest disturbances were conducted. The placing of the 9 measuring points was randomized with an angel from 0 to 360 degrees and a distance from zero to 50 m for every plot, giving a total of 36 points.

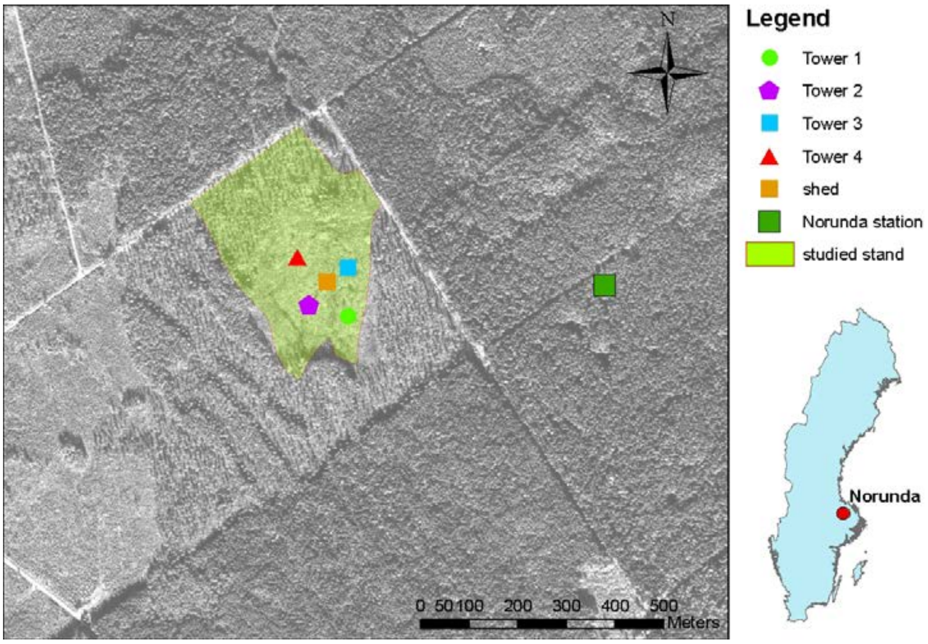


Figure 3.1. The site with the four individual plots, the different symbols displaying the towers in the middle of each plot. Also showing distance to Norunda station.

When random values fell within water areas or on areas where obstacles would prevent measurements, the point was moved. At first hand the point was moved 20 cm from the original location, if that did not help the point was moved an additional 20 cm, up to a maximum movement of 1 meter. Otherwise a new randomized value was compiled.

The area is rather flat, but due to higher ground water after felling small differences in elevation gives high variations in soil moisture and with large pools of water covering the ground at its lower points (fig 3.2). The clear-cut area was covered with logging residues and sparsely covered with growing vegetation, mainly grass and mosses.

Figure 3.2. Picture showing the diverse look of the clear-cut area, with a larger pool of groundwater.

3.3 Field measurements and data analysis

3.3.1 Biomass measurements and stump positioning

In late September 2009, 16 spruces and 16 pines in the stand bordering the clear-cut area were measured regarding stump diameter and breast height diameter. The stem diameters were measured at breast-height (130 cm) and at three different heights (20, 30 and 40 cm) closer to the ground for optimal representation of stump heights at the clear-cut area. From the measured stump and breast height diameter it was possible to derive a relationship between them using linear regression. This resulted in three equations for three different stump heights, for each species. The stumps on the clear-cut area were therefore sorted within three height intervals.

0-25 cm → 20 cm
26-35 cm →30 cm
36 cm or higher → 40 cm

All stumps in plot 2, with a diameter above 20 cm, were measured, both in diameter and height. Every stump was measured two times and average values were calculated. The species was noted and the stump position recorded using a tachymeter (fig. 3.3).

By using the derived relationships between stump and breast-height diameter from the surrounding stand, a theoretical breast height diameter for each stump was calculated. When all stumps in plot 2 were positioned and measured the biomass could be compiled using Marklund's equations combined with the calculated breast height diameter. Marklund's (1988) study resulted in specific equations given to each tree component and species (Table 3.1).


Fig. 3.3 Tachymeter measurements.

Table 3.1. Marklund's equations for Spruce and Pine.

	Spruce	Pine
Stump root system	$e^{(10,5381*\frac{d}{d+14}-2,4447)}$	$e^{(11,1106*\frac{d}{d+12}-3,3913)}$
Stem	$e^{(11,3341*\frac{d}{d+14}-2,0571)}$	$e^{(11,3264*\frac{d}{d+13}-2,3388)}$
Needles	$e^{(7,8171*\frac{d}{d+12}-1,9602)}$	$e^{(7,7681*\frac{d}{d+7}-3,7983)}$
Dead branches	$e^{(9,955*\frac{d}{d+18}-4,3308)}$	$e^{(9,5938*\frac{d}{d+10}-5,3338)}$
Living branches	$e^{(8,5242*\frac{d}{d+13}-1,2804)}$	$e^{(9,1015*\frac{d}{d+10}-2,8604)}$

When the theoretical breast height for the stumps was calculated the stump biomass could be derived. Through Marklund's equations it was possible to calculate the biomass of the harvested parts of the trees as well.

3.3.2 Soil carbon and nitrogen

In cooperation with the Swedish University of Agricultural Sciences SLU, Uppsala (Tryggve Persson) soil carbon and nitrogen stocks were measured. Soil samples were collected on October 6 2009 from the litter (L) layer, humus (FH) layer, 0-10 and 10-20 cm mineral soil layers. This was conducted for every plot, at the first six randomized measuring points. This was the last step in the field study since sampling soil is a great disturbance. The sub-samples at different depths were taken below each other to get an unbroken soil profile. Depending on the amount of logging residues the spot was covered of the L layer varied in thickness. The L samples were taken with a 250 cm^2 ring, the FH samples with a 10x10 cm frame, and the mineral soil samples were taken with a 45 mm diameter soil corer (15.9 cm^2 cutting edge). Samples from the L and FH layers were treated separately, whereas samples from the mineral soil layers were pooled two by two to form a composite sample.

The samples were kept fresh at 5 °C before analysis began. The litter layers were sorted from twigs, mosses and vascular plants and the FH material was sieved through a 5 mm mesh, removing stones, roots and branches. The mineral soil was sieved through a 2 mm mesh. After drying the samples, dry weight and total C and N content were determined. For further description see "Methods at Norunda" (T. Persson) in Appendix 1.

3.3.3 Chamber and eddy covariance measurements

For soil respiration measurements, collars were placed on each of the 36 measuring points. The collars had a diameter of 10 cm. They were pushed into the ground 2-5 centimetres to keep tight against the soil. Average inside height for every ring was measured for calculating the volume of the ring. CO_2 measurements started August 27 and continued through September 25, 2009. The measurements were performed with a mobile soil respiration system consisting of a gas analyzer (EGM-4, PP-systems, Hitchin, England) and a soil respiration chamber (SRC-1, PP-systems, Hitchin, England). Attached to the mobile soil respiration system was a thermometer (STP-1, PP-systems, Hitchin, England) measuring soil temperature at a depth of 0-10 cm. The equipment was calibrated with calibration gas with a known concentration before measurements began.

Fig. 3.4 showing a collar and the soil respiration system.

The chamber covered a surface area of 83 cm^2. The measurements started directly when the chamber was placed on the frame. Each measurement cycle was 80 sec, with a measurement every forth second. The efflux F [µmol m^{-2} s^{-1}] of CO_2 was calculated as

$$F = k \cdot \frac{V}{A}$$

Where k is the rate of change of [CO_2] over time [µmol m^{-3} s^{-1}], V is the total volume of the chamber and ring [m^3] and A the area of the ring [m^2].

Original data was given in ppm [µmol mol^{-1}] and to calculate C data was converted to µmol m^{-3} using following equation

$$C = C_{raw} \cdot \frac{P_{air}}{R \cdot (T_s + 273.15)}$$

where C is CO_2 concentration [µmol m^{-3}], C_{raw} is raw CO_2 concentration [µmol mol^{-1}], P_{air} is ambient air pressure [Pa], R is the universal gas constant [8.3145 J mol^{-1} K^{-1}] and T_s is soil temperature [°C].

In order to compare chamber fluxes to other fluxes and results the fluxes were normalized to a soil temperature of 10 °C.

$$R_{10} = R_i \bullet Q_{10}{}^{((10-T)/10)}$$

where R_{10} is the respiration rate at 10°C, R_i the measured respiration rate (=F) and T the measured soil temperature [°C]. Q_{10} was assumed to be 2, i.e. the respiration rate was assumed to double for an increase in soil temperature by 10°C.

During the time span of this study eddy covariance (EC) measurements were started (September 2009). Eddy covariance measurements are used to estimate vertical turbulent fluxes, such as water vapor, carbon dioxide and heat (sensible and latent), to or from the ground. In plot 3 a 3 m high tower were placed, where turbulent fluxes of [CO_2] and [H_2O] were measured by a LI-COR 7500 (LI-COR, Inc., Lincoln, NE, USA) and a Gill Windmaster sonic anemometer (Gill Instruments Ltd, Lymington, England). These measurements were used as a reference to validate the results of the chamber measurements.

3.3.4 Secondary measurements

The measurement points in each plot, except plot 1, were analyzed in regard to logging residues coverage and disturbance. Snowfall prevented all four areas to undergo this analysis. Coverage was estimated in percent while the disturbance was estimated as either non-existing or existing. This extensive information of the site gave an ability to link the respiration to site disturbances and the varied amount of logging residues.

4. Results and discussion

4.1 Stumps – relationships and distribution

The relationships between breast height and stump height diameters were determined for three different stump heights, this to get a more precise equation to fit to the stumps on the clear-cut area. For both spruce and pine, stump heights of 20, 30 and 40 cm were regarded. Figure 4.1 a-c show the relationships for pine while d-f show the relationships for spruce. Using these different equations depending on species and stump height all the measured stumps in area 2 got a calculated breast height diameter.

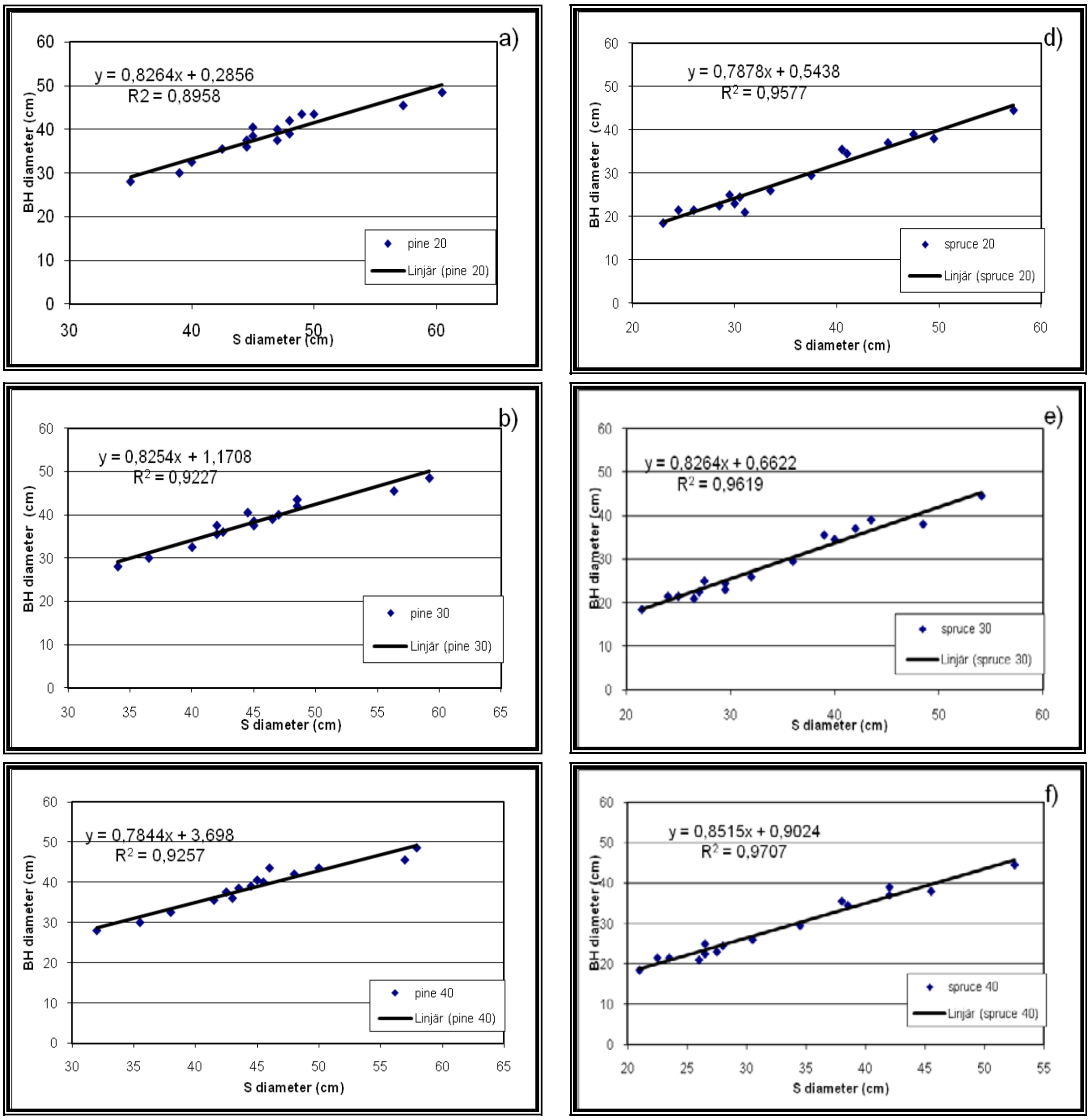


Figure 4.1. Graphs displaying the relationships between stump diameter (x-axis) and breast height diameter (y-axis) at three different stump heights. a) Pine at 20 cm, b) Pine at 30 cm, c) Pine at 40 cm, d) Spruce at 20 cm, e) Spruce at 30 cm and f) Spruce at 40 cm. With equations and R^2-values.

The relationships are linear and are showing a higher R^2 value with the higher stump heights. Perhaps the symmetry of the stem is more pronounced on the higher part of the stump and close to the ground the stem is rough and less cylindrical.

Plot 2 was ca 0.8 hectare and contained 425 stumps (with a diameter above 20 cm). That gave an average of 540 trees per hectare for the area. In figure 4.2 the distribution of spruce and pine is illustrated. Plot 2 also contained a small amount of birch. These were not of interest regarding biomass, but were included in positioning and the spatial distribution. The figure shows that pine was the most common species in plot 2. 75% of all trees were pine. Larger gaps were found at the outskirts of the plot, especially in the southern part. In these areas large water puddles were located and the stumps were therefore fewer, even though some could be found in the puddles. Finding stumps in puddles show that the water table is higher after the clear-cutting. Trees do not grow in puddles.

It is reasonable to assume that the species distribution and stump size distribution in plot 2 are representative for all four plots at the clear-cut.

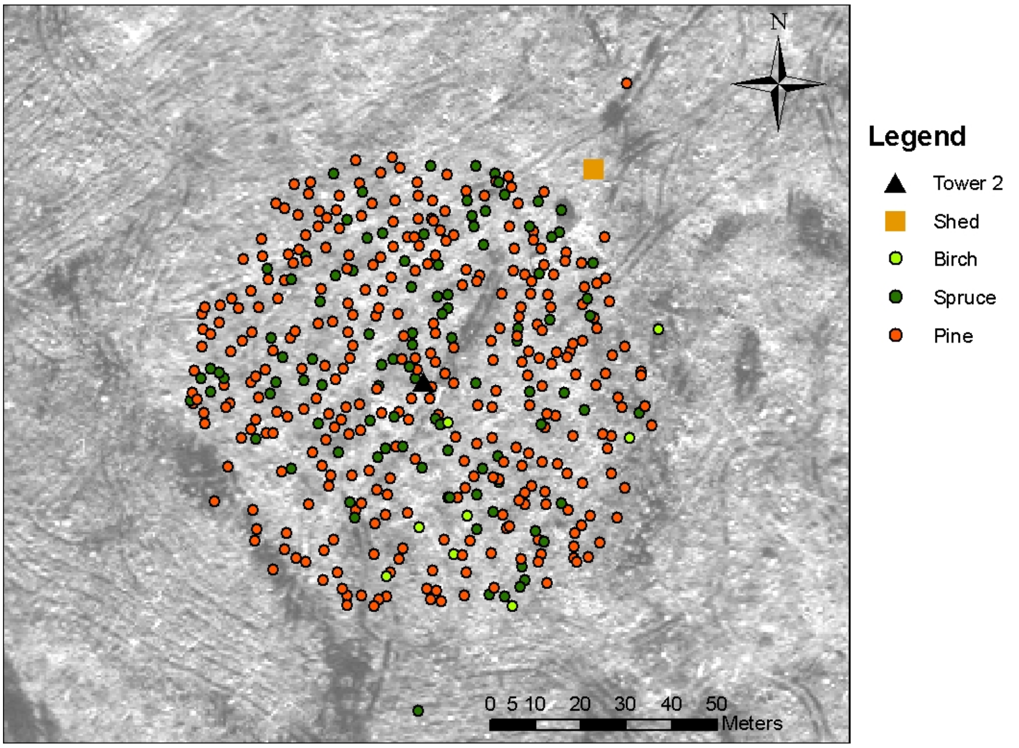


Figure 4.2. Distribution of spruce (red), pine (dark green) and birch (green) in plot 2. Black spots show the 9 measurement points for soil respiration at this plot.

Positioning of the stumps also gave information of the variation in ground surface height over the area. Figure 4.3 illustrates the varied terrain. The highest ground surface was found at the outskirts of plot 2, which was dominated by spruce. It should be noted that this distribution and height variation is only based on presence of stumps wider than 20 cm in diameter. It is not a complete height profile of the area. The height of the ground surface surrounding the stumps should rather be viewed as a helpful parameter to analyze the distribution of stumps and the species composition.

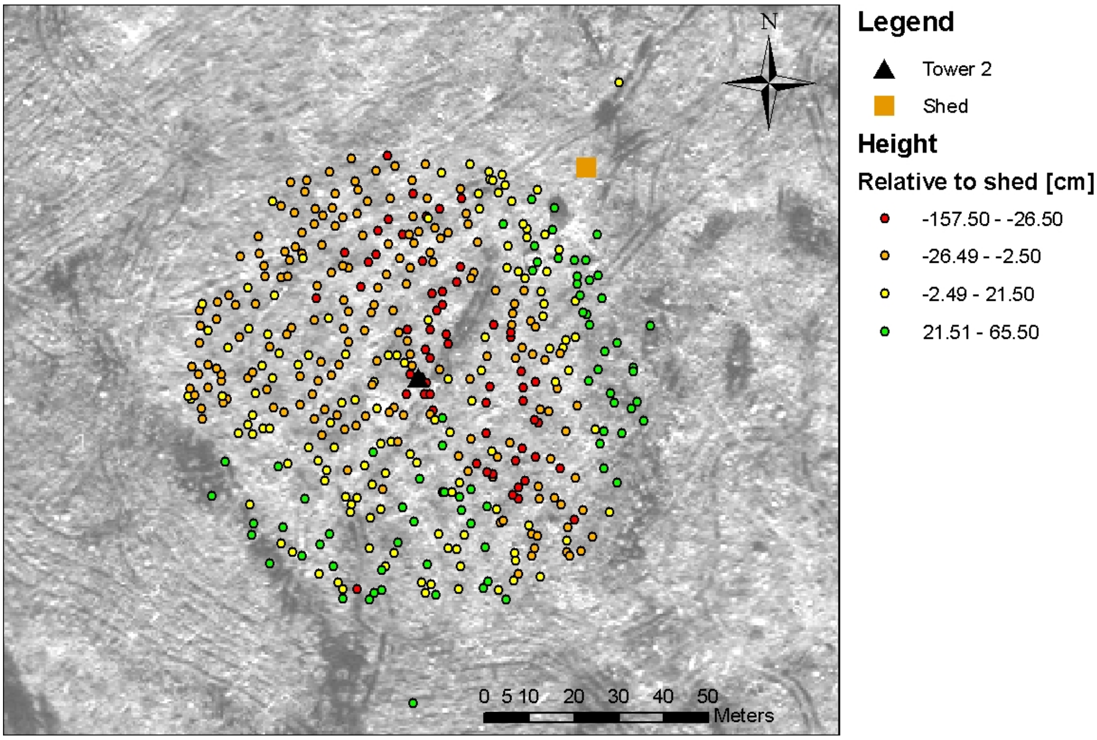


Figure 4.3. Ground surface height differences (cm) for plot 2. Red dots show the lowest heights and green dots the highest. Values are in cm and the ground by the shed is set as height reference.

4.2 Carbon and nitrogen stocks

4.2.1 Soil

Table 4.1 shows carbon and nitrogen stocks for 6 locations in each of the 4 plots, summing up to 24 soil measuring points. Points 1.6 and 4.5 had the largest stocks of carbon in the top 20 cm layers of the soil, with 18.55 kg Cm^{-2}. The largest nitrogen stocks are found in the same points, with about 0.65 kg Nm^{-2}. Point 3.1 holds the smallest amount of carbon, only 6.9 kg Cm^{-2}. Although, this point does not hold the smallest amount of nitrogen, point 2.9 contains only 0.26 kg Nm^{-2}. The range in both carbon and nitrogen stocks over the site is rather high. The carbon stock more than doubles from the lowest point to the highest.

Table 4.2 shows that plot 1 and 4 hold the largest amounts of both carbon and nitrogen, about 15.5 kg Cm^{-2} and 0.53 kg N/m^2. Table 4.1 clearly shows that more or less all points have a C/N ratio within the range of optimal decomposition.

Table 4.1 Carbon/Nitrogen stock in LFH+0-20 cm deep in soil, and C/N ratio.

	kg C m-2	kg N m-2	C/N ratio
1:1	14,4	0,6	25,8
1:2	15,7	0,6	24,6
1:3	17,0	0,5	31,4
1:7	17,7	0,6	29,6
1:5	10,7	0,4	26,3
1:6	18,6	0,7	27,6
2:1	14,8	0,5	30,2
2:2	16,1	0,5	30,2
2:3	9,5	0,3	30,1
2:4	13,1	0,4	33,2
2:9	8,6	0,3	32,6
2:6	12,8	0,4	32,5
3:1	6,9	0,3	23,2
3:2	9,6	0,4	26,9
3:3	14,0	0,5	30,8
3:4	14,8	0,5	32,1
3:5	9,7	0,4	23,8
3:6	12,7	0,5	24,7
4:1	15,0	0,5	29,9
4:2	15,8	0,5	30,1
4:3	15,4	0,5	31,4
4:4	14,3	0,5	28,1
4:5	18,6	0,6	30,6
4:6	14,2	0,5	27,4

Table 4.2 Average values of carbon and nitrogen stocks plus C/N ratio for the different plots, with standard error

	kg C m^{-2}		kg N m^{-2}		C/N ratio	
	Average	**Std error**	**Average**	**Std error**	**Average**	**Std error**
Plot 1	15,68	1,17	0,57	0,04	27,53	1,04
Plot 2	12,48	1,20	0,40	0,04	31,45	0,59
Plot 3	11,29	1,24	0,42	0,03	26,91	1,54
Plot 4	15,53	0,66	0,52	0,02	29,60	0,62
Total area	13,75	0,65	0,48	0,02	28,87	0,61

According to T. Persson (pers.com. Feb. 2010), carbon and nitrogen stocks are rather high for this area. Expected carbon stock would be around 7 kgm^{-2}, and on this site almost 14 kg Cm^{-2} is found on average. The area contains 0.48 kg Nm^{-2}. These values correspond to forests in Halland and Skåne. They are expected to be half as big in Uppland. The C/N ratios are higher than expected but that could be a result of that smaller branches might have been mixed with needles during the soil sampling. Wood holds small amounts of nitrogen, therefore a higher ratio. The soil contains large amounts of carbon and nitrogen and the C/N ratio is within the limits for optimal decomposition. Given these results there are no indications that these factors could limit decomposition.

4.2.2 Biomass

Marklund's equations (table 3.1) for pine and spruce were combined with the stumps calculated theoretical breast height diameter, and this allowed for an estimation of the stumps dry biomass (including their root systems) at plot 2. Pine held most of the plot's biomass. All pine biomass equaled 32 380 kg whereas the total spruce biomass was only 7 850 kg. This indicate a total pine biomass of 40.5 ton/ha and a total spruce biomass of 9.8 ton/ha. Thus, the total amount of stump biomass was 50.3 ton/ha.

Assuming that stump biomass has the same heat value as firewood (Näslund Eriksson & Gustavsson, 2008), i.e. 3.8 MWh/ton dry matter, gives an energy potential of 190 MWh/ha. Earlier studies have found energy potential from stumps to be 170-250 MWh/ha (Nylund, 2005; Rolfsson, 2006).

With the calculated breast height diameter for each stump other parts of the (now harvested) trees could be estimated. With each part of the tree calculated, a better understanding of the remaining amounts of biomass was given. In figures 4.4 and 4.5, the biomass distribution for spruce and pine is shown, according to Marklund's theories. Pine has a higher biomass density than spruce. 80% of all biomass in plot 2 was found in pine stumps while only 75% of the stumps at the plot were pine.

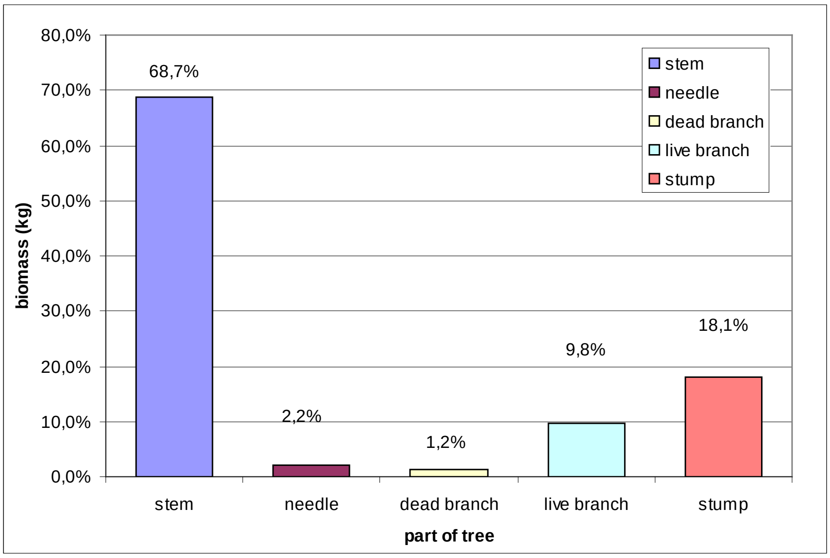


Figure 4.4. Biomass distribution of pine at plot 2. The stem holds large parts of the biomass, leaving 18% of the tree biomass in the stump after harvest.

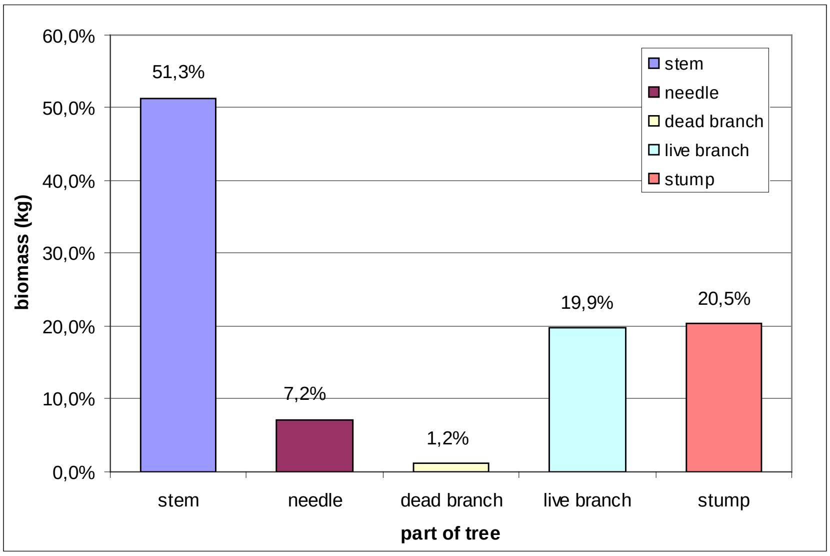


Figure 4.5. Biomass distribution of spruce at plot 2. Half of the tree biomass is kept in the stem but almost as much is found in the live branches and the stump. 20% of the biomass is left in the stump after harvest.

Marklund's studies showed that pine keeps a much larger part of its biomass in the stem than spruce do. Spruce holds much more biomass in its branches and needles than pine do. Both pine and spruce had approximately the same amount of biomass in their stumps. According to the calculated values, plot 2 once contained almost 220 tons of biomass. Today the area only holds 40 ton. That gives a remaining amount of 18%, which correlates with published facts (web source [2]).

The distribution of biomass is visualized in figure 4.6. The bigger biomass clusters are found in the lower parts. The distribution of the trees could affect the size of each tree. If the trees stood close they could limit each other. It is clearly shown that the area is dominated of pine, but that the stumps with highest biomass are spruce.

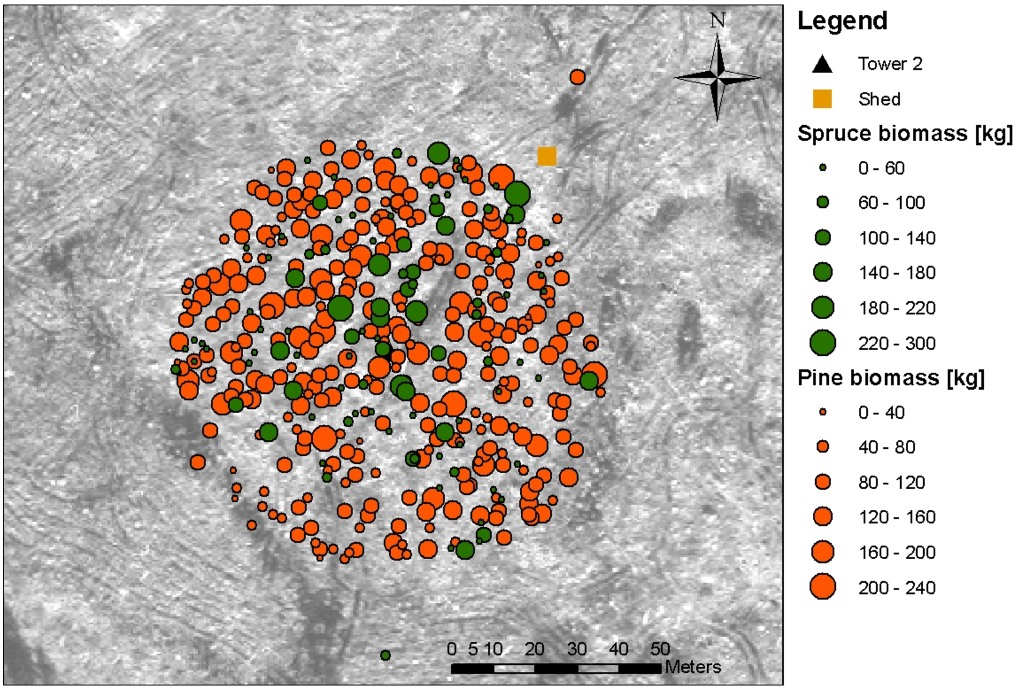


Figure 4.6. Biomass (kg) distribution and variation for spruce and pine.

4.3 CO_2 fluxes

4.3.1 Chamber measurements

During the field study each of the 36 measurement points was measured regarding soil respiration 13 times, from the 27th of August through 25th of September. Each plot got an average emission for every time a field measure was conducted, displayed over time. Figure 4.7 shows that all plots decrease their emissions of CO_2 over time and that there were a notable spatial and temporal variability of the emissions at all four plots. They all have a rather high spatial variability, especially for the early measurements. Emissions from plot 4 have high spatial variability throughout the field study. Looking at plot 3, it has a more stable decrease in CO_2 emissions over time and also a lower spatial variability. Emissions are linked to the decrease in soil temperature. Over this specific time span the soil temperature had an average decrease of 7 °C, but the largest portion of the decrease occurred during the last days of the field study.

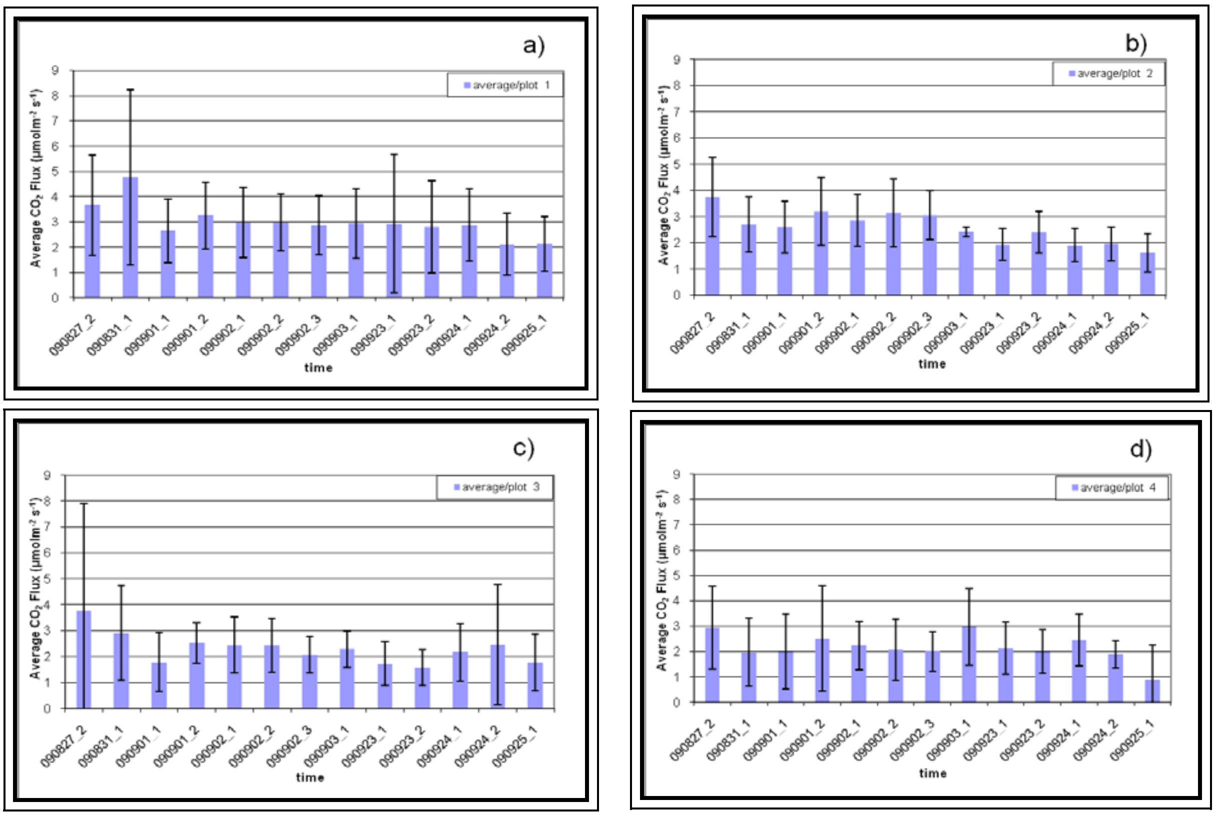


Figure 4.7. a) Average CO_2 emissions over time at plot 1 b) Average CO_2 emissions over time at plot 2. c) Average CO_2 emissions over time at plot 3. d) Average CO_2 emissions over time at plot 4. Black bars denote standard deviation (i.e., the spatial variability in CO_2 emissions)

For every measured point (summing up to 36 points), a mean value of CO_2 emissions were calculated (see fig. 4.8) The mean emission for all the measured points was 2.48 µmol m^{-2} s^{-1}. Kowalski *et al.* (2004) studied respiration on several clear-cut European sites. The respiration on these sites varied from 2.15 to 7.25 µmol m^{-2} s^{-1}. Those measurements were all conducted during the month of June, probably explaining the higher respiration rates than this study presents.

Figure 4.8 shows the spatial variation of the measurement points and the average emission from each of them. It is difficult to find a clear trend over the site. Perhaps there are higher emissions on the western part of the site. Figure 4.9 also displays the average emissions, without the spatial variation. Some measurement points had significantly higher respiration rates than the average. For example, point 1.2 with a mean emission of 5.6 µmol m^{-2} s^{-1}. This point was located on flat ground with large amounts of cutting residues and limited moisture, which could explain the higher emissions. Point 2.4 had a mean emission of 4.6 µmol m^{-2} s^{-1} and was located on flat ground with sparse amounts of cutting residues. Higher than average but not as easily explained only looking at the surroundings. Many factors are to be considered to explain the higher emissions, soil moisture being one of the more important factors. Other factors affecting the measured emissions were carbon and nitrogen stocks in soil and microbial activity in the specific point. Points located on soil covered sparsely with cutting residues got more exposure to the sun and therefore slightly higher soil temperatures stimulating the microbial activity. The degree of disturbance on the specific soil could also affect the emissions. Disturbance of some degree can give higher soil activity, mainly due to the increase of oxygen. But with a too large damage to the ground the erosion becomes big and leaching of toxic mercury could be of issue (Skogsstyrelsen, 2009).

When comparing the four different plots (fig. 4.10) in regard of respiration rates, it is clear that the two northern plots (3, 4) have lower emissions than the southern ones. Looking at the visible ground water table plots 1 and 3 are moister, while 2 and 4 are rather dry. Figure 4.10 indicates that soil moisture is not the only factor affecting these processes. Methane (CH_4) emissions were not studied but the rather large and frequent water puddles indicated high soil moisture which could limit the CO_2 emissions and result in CH_4 production.

In table 4.3 mean soil respiration rates for the four plots are presented in numbers, with corresponding standard deviations. The differences in respiration rates between the plots are small and the standard deviations are somewhat equal. Area 1 with the highest average emission also presents the highest standard deviation.

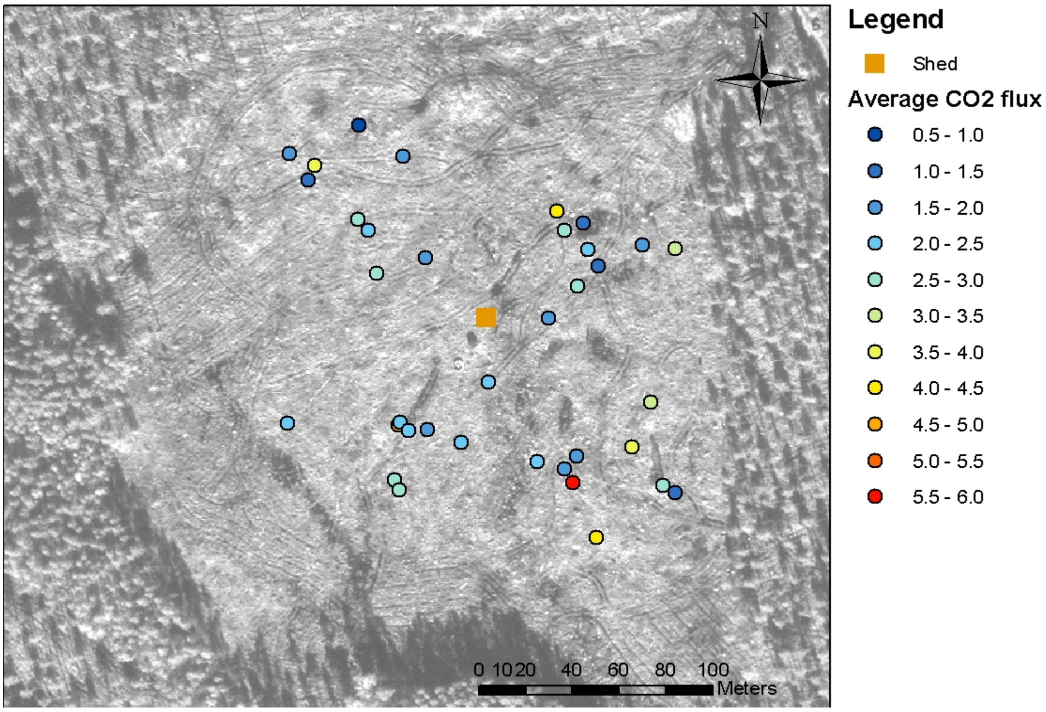


Figure 4.8 Spatial variation of average CO_2 emissions for every measurement point at the clear-cut area.

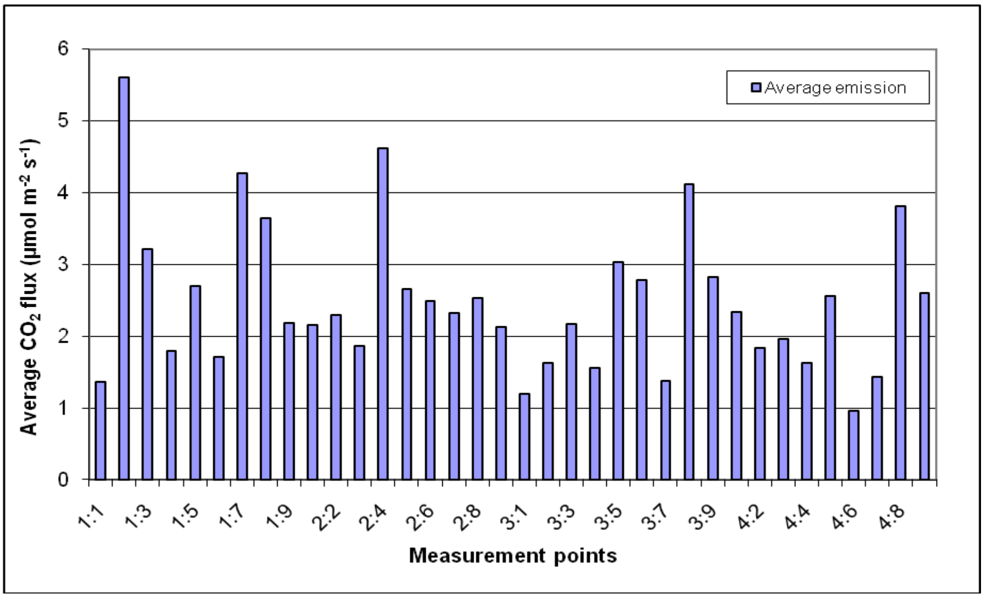


Figure 4.9. Average CO_2 emissions for every measurement point at the clear-cut area.

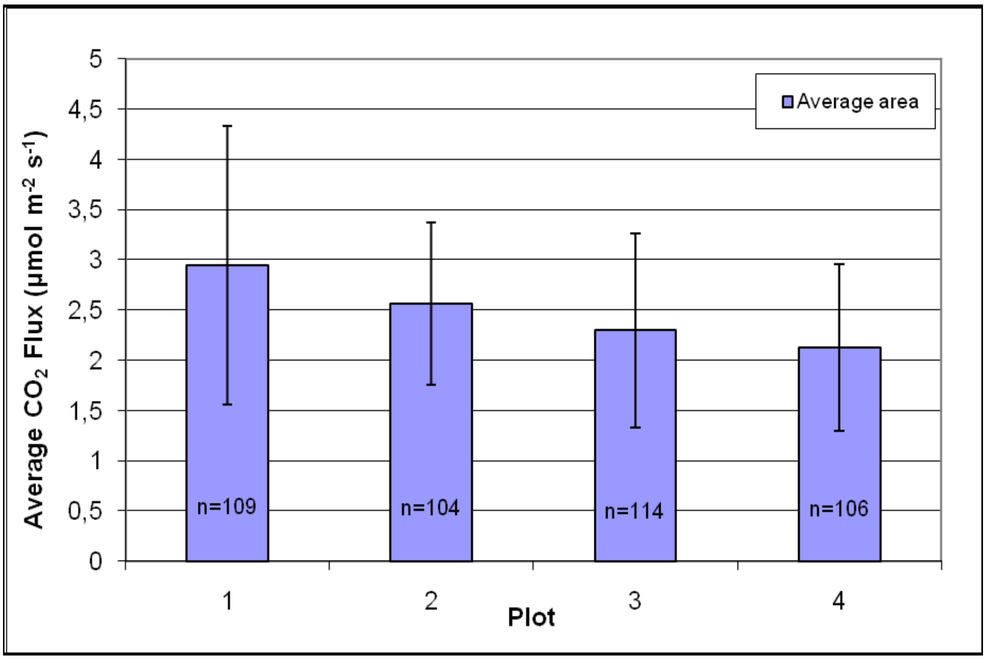


Figure 4.10 Average CO_2 emissions at the four different plots.

Table 4.3. Average CO_2 flux (µmol m^{-2} s^{-1}) and std for the four plots.

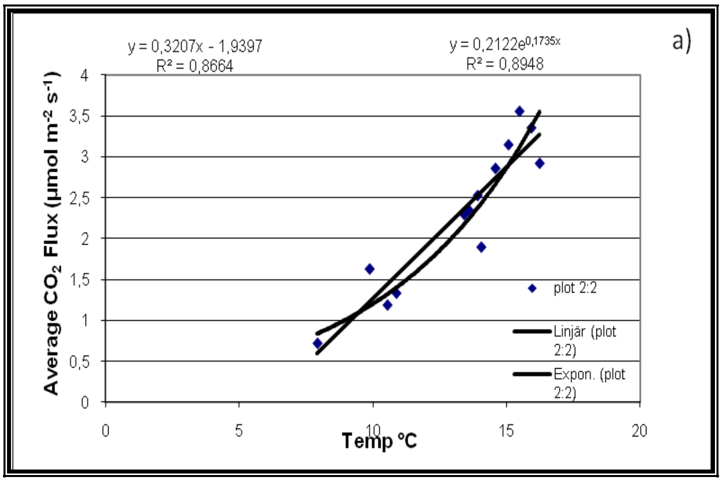
Plot	Average (µmol m^{-2} s^{-1})	Std (µmol m^{-2} s^{-1})
1	2,94	1,39
2	2,56	0,81
3	2,30	0,97
4	2,12	0,83

Table 4.4 R^2 values (linear and exponential fits) for each

	R^2 linear	R^2 exp
1:1	0,03	0,008
1:2	0,005	0,003
1:3	0,78	0,73
1:4	0,41	0,34
1:5	0,20	0,30
1:6	0,63	0,65
1:7	0,29	0,49
1:8	0,05	0,09
1:9	0,14	0,18
2:1	0,20	0,18
2:2	0,87	0,89
2:3	0,43	0,39
2:4	0,37	0,33
2:5	0,75	0,75
2:6	0,24	0,16
2:7	0,17	0,14
2:8	0,03	0,03
2:9	0,45	0,44
3:1	0,14	0,15
3:2	0,04	0,05
3:3	0,22	0,03
3:4	0,24	0,14
3:5	0,10	0,14
3:6	0,64	0,71
3:7	0,02	0,03
3:8	0,10	0,15
3:9	0,21	0,07
4:1	0,26	0,28
4:2	0,00004	0,009
4:3	0,01	N/A
4:4	0,01	N/A
4:5	0,19	0,06
4:6	0,004	N/A
4:7	0,20	0,19
4:8	0,31	0,26
4:9	0,57	0,67

Temperature dependence

When the emissions are analyzed in regard of soil temperature, correlations are found in only some of the points. Figure 4.11 illustrates one good modulation and one bad regarding temperature dependence of CO_2 emissions.



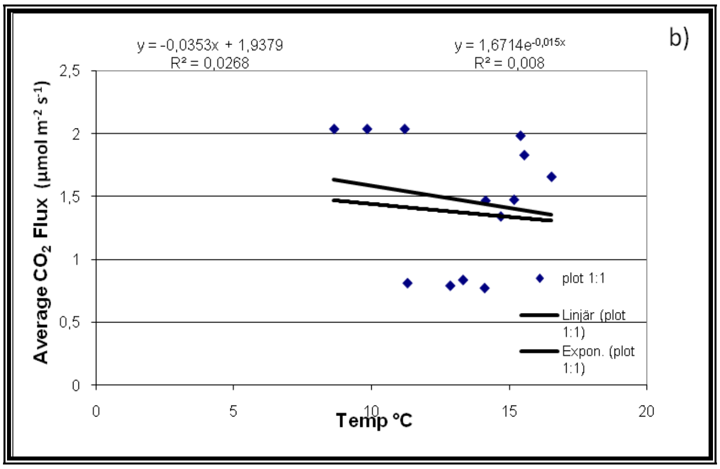


Figure 4.11 Correlation between CO_2 emissions and soil temperature a) Point 2.2 showing good correlation, both for linear and exponential trends, b) point 1.1 showing a rather bad correlation.
Left equation corresponds to the linear trend, whereas the right equation shows the exponential trend.

Table 4.4 shows R^2 values for both linear and exponential modulation for all the points. There are not too many points showing correlation between soil temperature and emissions. Soil temperature is the primary controlling factor in regard of emissions, only in extreme drought or extreme moisture does it limit the emissions (Kowalski *et al.*, 2004). Unfortunately was no data for the soil moisture collected during the field study. Since the site visually looked wet there is a possibility that CH_4 production took place and that could explain the many points in where soil temperature did not correlate with the CO_2 emissions. Possibly could the disturbance of the clear-cutting have impacted the ground severely and thereby affected the CO_2 emissions.

4.3.2 Eddy Covariance

A short period after the chamber measurements started, eddy covariance (EC) equipment was placed in the tower in plot 3. The measurements started in the beginning of September 2009. Due to simultaneous measurements at the same plot, EC data could be used to validate the chamber results. Four dates during September could be used for a comparison of the CO_2 fluxes (fig. 4.12).

For the 23th and 24th of September two chamber measurements per day were conducted. There is a good agreement between the chamber measurements and the eddy covariance measurements. The chamber measurements were conducted with a closed (dark) chamber giving only soil respiration. EC measures the net flow - respiration and CO_2 uptake. During that time of year the uptake is low but the EC measurements should have a bit lower results than the chamber measurements.

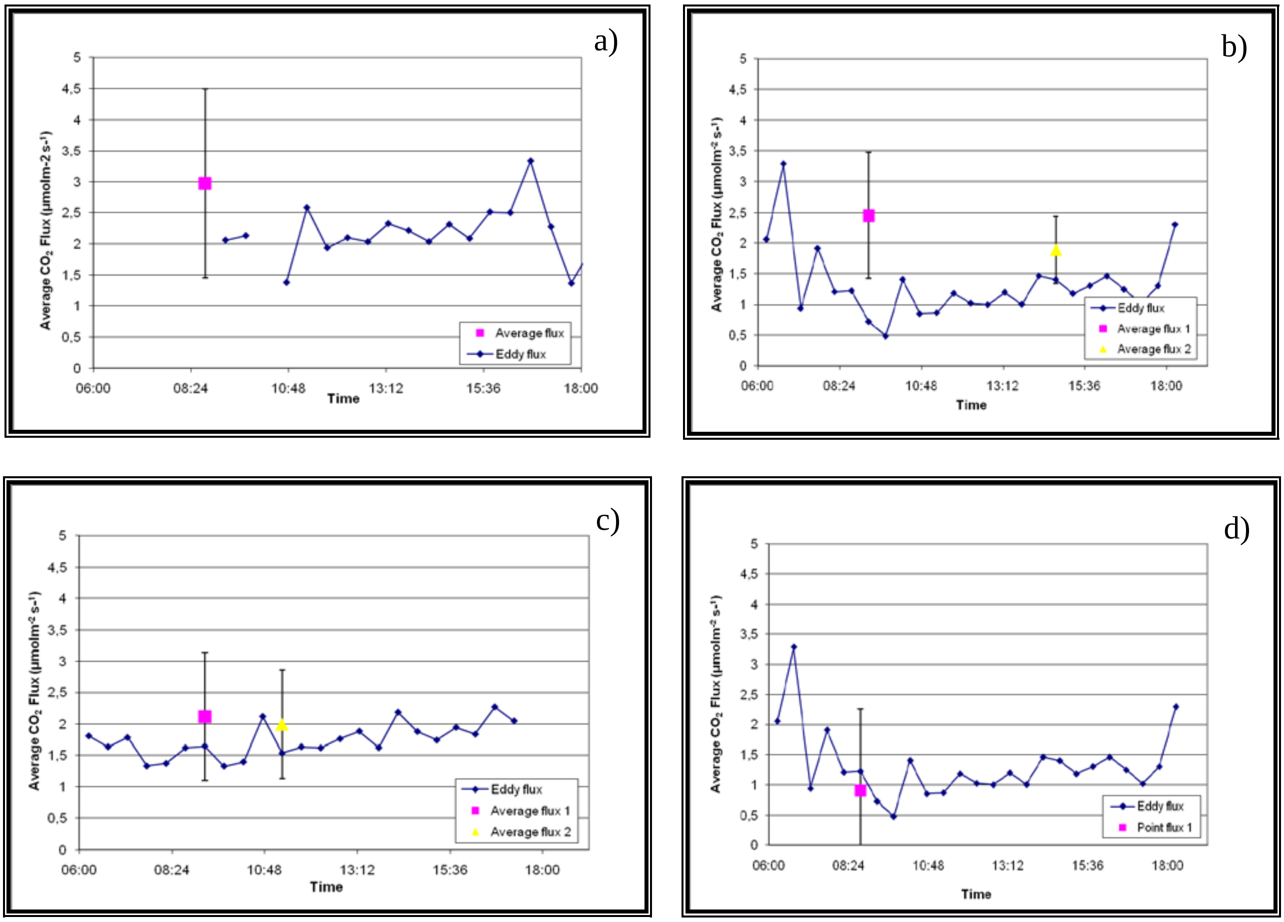


Figure 4.12 Chamber measurements compared to eddy covariance measurements from a) the 3rd of September 2009. Due to EC data being quality controlled holes in the series occur b) the 23rd of September 2009. During this date the chamber measurements were executed twice c) the 24th of September 2009. During this date the chamber measurements were executed twice d) the 25th of September 2009.

4.3.3 Emissions – forest vs. clear cut area

During June 2007 Pavelka *et al*. studied CO_2 emissions at the floor of a forest site at Norunda. The experimental site was divided into a grid of 10x10 m. Within this area 72 collars were placed. Soil respiration measurements were performed using a system consisting of gas analyzer (Li-6200) with a home-made soil respiration chamber. (See appendix 2 for further details.)

Table 4.5 Average emissions for the 4 plots on the clear cut area and in the nearby forest.

	Average (μmol m^{-2} s^{-1})	**Std** (μmol m^{-2} s^{-1})
Plot 1	2,36	1,45
Plot 2	1,20	0,72
Plot 3	1,80	1,28
Plot 4	1,72	1,01
Forest (Pavelka *et al.*)	2,09	0,45

By comparing R_{10} values, i.e. the respiration rates at 10°C, from the two sites, it is possible to put this study in relation to other studies in the nearby forest. One major difference between the two sites is that in the forest both autotrophic (belowground and aboveground) and heterotrophic respiration takes place. At the clear-cut site there is mainly heterotrophic respiration since all the trees has been removed and there is not much ground vegetation. You could therefore expect the clear-cut area to have significantly lower CO_2 emissions, since belowground autotrophic respiration normally accounts for 20-60% of total soil respiration (Widén and Majdi, 2001). That is clearly not the case (table 4.5). The reference emissions are not much higher than the emissions at plot 3 and 4, and plot 1 even has a higher average emission than the reference. Although, the standard deviation for the forest emissions are much lower, showing a more homogeneous set of measurement results. Kowalski *et al.* (2004) studied respiration rates from both mature stands and clear-cut sites in four different European countries. The respiration between mature and clear-cut stands showed little difference. The assumption of Q_{10} set to 2 does not need to be correct, especially a clear-cut indicate to have higher temperature sensitivity.

4.3.4 Disturbance affecting emissions

All measurement points in plots 2, 3 and 4 were analyzed regarding logging residue coverage of the ground. Depending on how many percent of the ground that was covered with residues, the measurement point was sorted into one of five equally big classes. Average emission and standard deviation for each class was compiled. Figure 4.13 and table 4.6 show average emission for each of the five different classes. A higher coverage gives a higher average emission. When the ground was highly covered with logging residues (>80%), the average emission was much higher. Although, it should be mentioned that only two measuring points were covered with at least 80% of logging residues. Half of all the points (n=14) were covered with less than 20% of residues. This highlights the importance of having many measurement points to obtain reliable statistics.

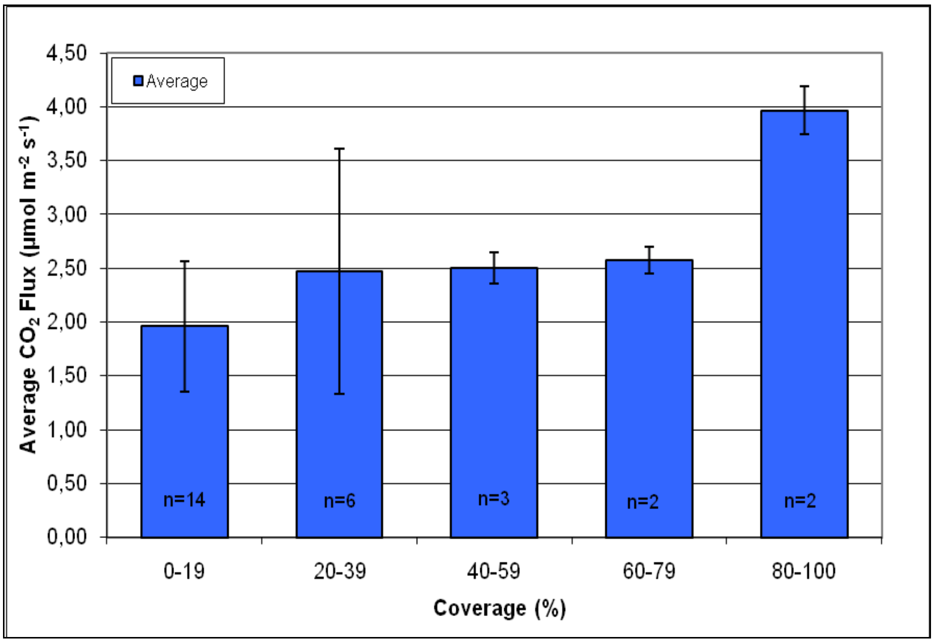


Figure 4.13 Average CO_2 emissions for each of the five residue coverage classes.

Table 4.6 Average CO_2 emissions in regard to logging residue coverage.

Class (%)	Average (µmol m^{-2}s^{-1})	Std (µmol m^{-2}s^{-1})	n
0-19	1,96	0,61	14
20-39	2,47	1,14	6
40-59	2,50	0,14	3
60-79	2,57	0,12	2
80-100	3,97	0,22	2

Statistical tests show that there is significant difference between the 5 classes in regard to average CO_2 emissions. When only including 4 of the classes (1-4 or 2-5) there is no significant difference. This means that class 1 (<20%) and/or class 5 (>80%) have a significantly different average CO_2 emission than the other classes.

Any statistical difference in CO_2 emissions between disturbed and undisturbed points was not found (table 4.7). But the ground on the site was probably largely affected by the clear-cutting and site preparation since half of the randomized points were subject to disturbance.

Table 4.7 Disturbance vs. CO_2 emissions.

Disturbance	Average (µmol m^{-2}s^{-1})	Std (µmol m^{-2}s^{-1})	n
yes	2,38	0,97	14
no	2,28	0,75	13

4.3.5 Soil carbon and nitrogen stocks in relation to emissions

By using measured carbon and nitrogen stocks, correlations between C and N stocks and CO_2 emissions were investigated. Figure 4.14 shows the correlation between carbon stocks and emissions, whereas figure 4.15 displays the correlation between nitrogen stocks and emissions.

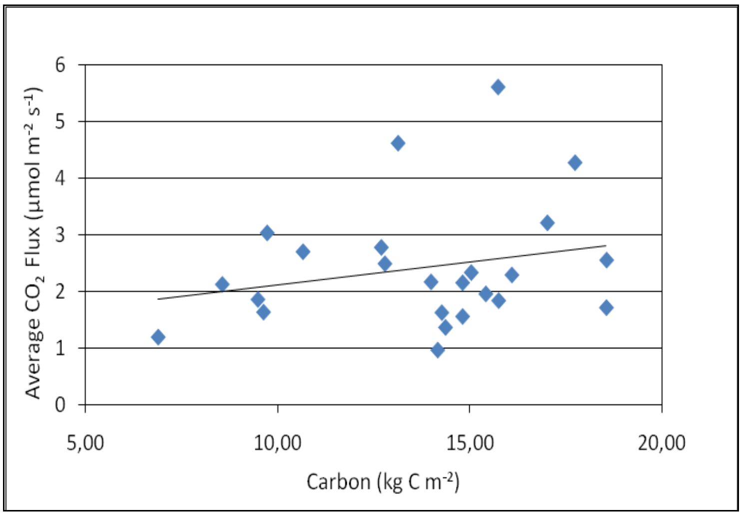


Figure 4.14 Correlation between CO_2 emissions and carbon stocks (down to 20 cm depth). R^2 value is 0.05.

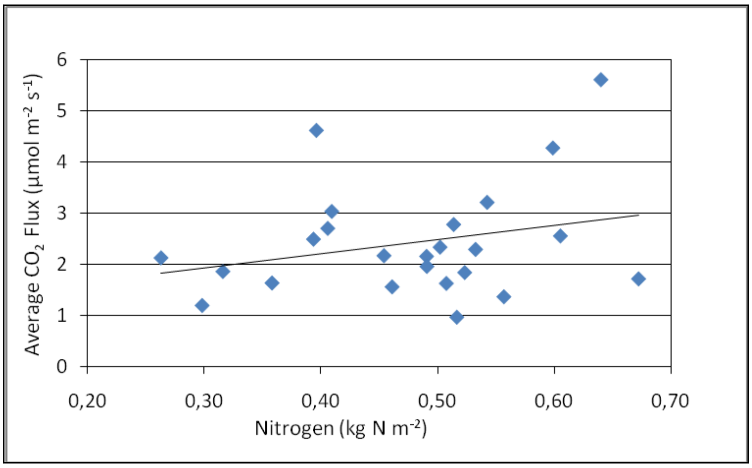


Figure 4.15 Correlation between CO_2 emissions and nitrogen stocks (down to 20 cm depth). R^2 value is 0.07.

In both figure 4.14 and 4.15 no clear trend could be found. Figure 4.16 illustrates the relationships between emissions and C/N ratio for each plot (1-4).

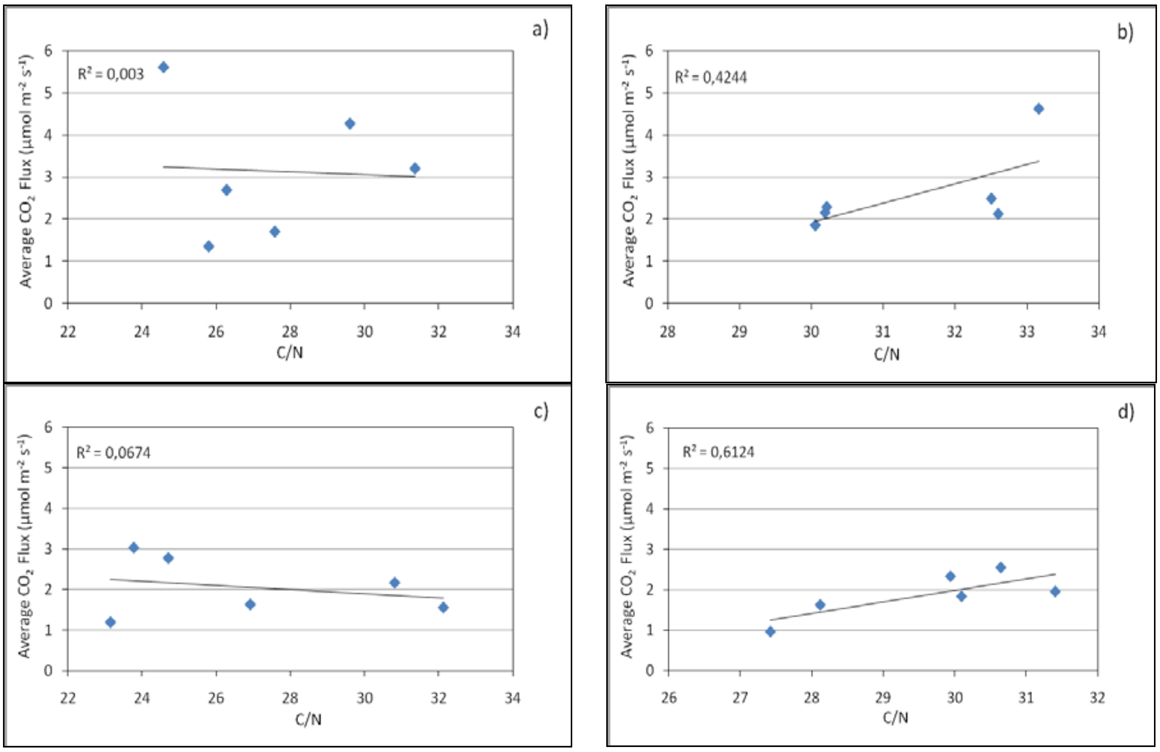


Figure 4.16 The relationship between CO_2 emissions and C/N ratio for a) plot 1 b) plot 2 c) plot 3 d) plot 4.

Figure 4.16 shows that plot 2 and 4 show rather good relationships between emissions and C/N ratio. Area 1 and 3 were moister and perhaps if they had been drier a correlation could have been found also in these areas. A large pool of carbon and nitrogen in the soil does not necessarily mean there are high emissions of CO_2. There are many factors affecting the process and these results. As mentioned, soil moisture could limit the emissions. The exact location of the soil sampling is also of interest. In some cases the soil sampling could not be conducted in the same spot as the soil respiration measurements, due to roots or stones in the ground. That adds uncertainty to the relationship between soil carbon/nitrogen and emissions, since the soil sample only reflects the reality for the exact spot it was taken. In addition, the area where the respiration measurements were conducted was not equal to the area the soil samples were gathered from, which also adds uncertainty to the analysis.

5. Conclusions

- During the autumn of 2009 plot 2 held approximately 40 ton of dry biomass (50 ton/ha) in the remaining stumps, equalling only 18% of what the pre-harvest forest originally contained. Once the area contained almost 220 ton.

- The energy potential of the stumps at plot 2 was 150 MWh; i.e., 190 MWh/ha.

- The site holds exceptional large stocks of both carbon (14 kg C/m^2) and nitrogen (0.48 kg N/m^2), which are twice the expected stocks for this region.

- The mean soil respiration rate for the site was 2.48 μmol m^{-2} s^{-1} during this period. This is in accordance with earlier studies in the area and with other clear-cuts.

- The CO_2 emissions decrease over time, and over the site the emissions vary with no clear trend.

- No distinct relationships were found between CO_2 emissions and soil temperature, ground disturbance or logging residue coverage, nor carbon and nitrogen stocks. There are likely more factors affecting emissions than what this study examined. Some of the carbon emissions could have been in the form of CH_4.

Acknowledgements

It is a great feeling to finally finish this Master Degree thesis, and naturally there are several people I need to give my thanks to, for in various ways providing me with support and making this possible. First of all there is my supervisor in the project, Patrik Vestin who helped me in every step and led me safely to land. He never gave up on me, and continued to encourage me all the way through. Anders Lindroth for introducing me to the subject and therefore opened my eyes to the extensive resource Swedish forests are. I have also had practical help from other staff members at our department at Lund University; Meelis Mölder for help both in Lund with various technical difficulties and providing me with EC data but also in Norunda for the entertaining stories and support with field measurements; Margareta Hellström for always being approachable and helpful with issues concerning ArcGIS and various other computer dilemmas; Fredrik Lagergren for instructing me with the right equations to use from Marklund's massive compilation. I would also like to thank Anders Båth at the Norunda station for all his help with stump positioning and excellent company in the depth of the forest. Tryggve Persson from SLU Uppsala helped me profoundly with soil sampling and lab treatment and then providing me with data. A great thanks to Monika Strömgren from SLU for lending me her soil respiration equipment. Marian Pavelka was kind enough to provide me with data for comparison. Moving on to a more personal room, the people closest to me – family and friends, have given me everyday support, encouragement and care.

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Appendix 1

Soil sampling

Soil samples were collected on 6 October 2009 from the litter (L) layer, humus (FH) layer (O_{e+a} horizon) and the 0-10 and 10-20 cm mineral soil layers at 6 spots within each of the 4 plots. The L layer varied in thickness from spot to spot depending on whether the spot had been covered by logging residues or not. Large heaps of logging residues resulted in high amounts of newly fallen needles and twigs. All sub-samples at different depths at the same spot were taken below each other to have the soil samples from an unbroken soil profile. The L samples were taken with a 250 cm^2 ring, the FH samples with a 10 cm x 10 cm frame, and the mineral soil samples were taken with a 45 mm diameter soil corer (15.9 cm^2 cutting edge). Samples from the L and FH layers were treated separately, whereas samples from the mineral soil layers were pooled two by two to form a composite sample.

Laboratory treatment

The soil samples were kept fresh at 5 ºC before sieving and weighing at room temperature. The L material was sorted free from twigs/branches larger than 10 mm diam. Green mosses and vascular plants were also removed. The FH material was sieved through a 5-mm mesh, whereby roots, stones and buried branches were sorted out. The mineral soil layers were sieved through a 2-mm mesh. Subsamples were removed from the sieved materials for determination of dry weight, KCl-extractable inorganic N and pH(H_2O). Dry matter was determined after drying at +105 ^{o}C for 24 h. Total C and N concentrations were determined in a Carlo-Erba NA 1500 Analyzer. Soil pH was measured in the supernatant after revolving flasks with a mixture of soil/distilled water (1:1 by volume) for 2 h followed by sedimentation and aeration for 22 h. Because soil pH was always below 6, we assumed that there was no carbonate C.

After sample preparation, which was finished after about 4 weeks from sampling, L, FH and mineral soil subsamples (corresponding to 6, 16 and 100 g dry wt, respectively) were placed in plastic jars (50 cm^2 surface area, 466 cm^3 volume). The jars had a lid with a 5-mm diameter aperture for gas exchange. These soil microcosms were incubated in the laboratory at constant temperature (15 ºC) and moisture (60% WHC, water-holding capacity) to determine C mineralisation (CO_2 evolution) and net N mineralisation and potential nitrification. A whole incubation period lasted for 21 days. CO_2 measurements were performed once a week to obtain mean respiration rates for the first 21 days, whereas net N mineralisation was estimated for the whole 21-day period (not reported in this study).

To determine C mineralisation, the containers were periodically closed with airtight lids with a rubber septum. Background gas samples were taken after 15 min from the headspace with a syringe and were injected into a gas chromatograph (Hewlett Packard 5890, H.P Company, Avondale, PA, USA). The measurement was repeated when an appropriate amount of CO_2 had accumulated in the jars, from 120 min to 24 h, depending on the respiration rate. The mass of C evolved per jar was calculated according to Persson et al. (1989) and data on the C pools in each soil layer enabled us to calculate C mineralisation rates per m^2. Because roots and mycorrhizal mycelia were almost entirely removed by sieving, and because there was a delay of 4 weeks between sampling and start of incubation, we considered the estimated C mineralisation to be of heterotrophic and not autotrophic origin.

Extrapolation to the field was made by multiplying the rates obtained in the laboratory (expressed per g of C) by (1) the amount of C per soil layer and (2) a temperature/moisture-dependent factor (C_C) with input data from (a) soil temperature and soil moisture measurements in the field and (b) a response function for temperature and moisture (given in Persson et al. 2000). The correction factor (C_C) for converting the rates obtained in the laboratory at 15°C to those in the field soil at Norunda was estimated to be 0.35.

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Appendix 2

Soil and understorey CO_2 efflux at Norunda site

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Method: The experimental site was divided into a grid (10x10 m). In each fixed position a ring (collar with dimensions 19 cm in diameter, height 8.5 cm) was placed and inserted into the soil about 3 cm deep. The total number of the rings was 72. The understory was not cut and not removed inside the rings. Another 20 rings were installed at the footprint place, in a grid (5X5 m).

Soil temperature was measured inside of each ring during efflux measurement by penetration thermometer (Roth, Germany) at 1.5 cm depth.

Soil and understory CO_2 efflux measurements were done using three identical systems consisting of gas analyzers (Li-6200)) and home-made soil respiration chambers. Measurements were performed during 7^{th} - 12^{th} of June 2007.

For each position, a set of 15 measurements were performed. Values of R_{10} (soil CO_2 efflux normalized to the temperature of 10°C) were calculated for each position to estimate soil (include understory) CO_2 efflux spatial heterogeneity. These values were calculated using Q_{10}=2. The average of R_{10} and SD for individual position was estimated. The table (xls-file) contains characterization of understory vegetation and distance from the closest trees and stumps.