Effects of Site Preparation and Stump Harvest on Carbon Dynamics in Forest Soils

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Doctoral Thesis
Swedish University of Agricultural Sciences
Uppsala 2015

Acta Universitatis agriculturae Sueciae
2015:69

ISSN 1652-6880
ISBN (print version) 978-91-576-8336-6
ISBN (electronic version) 978-91-576-8337-3
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Print: SLU Service/Repro, Uppsala 2015

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Abstract

Efforts are being made to substitute fossil fuels with renewable alternatives to address increasing concerns regarding global climate change driven by anthropogenic emissions of CO_2 and other greenhouse gases. Stumps of harvested trees could make a significant contribution to these efforts in Scandinavia. Silvicultural measures may all impact on greenhouse gas fluxes. Site preparation, being one of these, is conducted on a major share of the annual clear-cut area in Sweden to promote seedling development. More information on the effects of stump harvesting and site preparation methods, on soil and ecosystem C stocks is needed as all of these treatments disturb the soil, creating for instance areas of exposed mineral soil, and/or a double humus layer and/or a humus layer mixed with mineral soil. The overall aim of this thesis is to assess changes in C stocks (in soils and ecosystems overall) following several common mechanical site preparation methods and stump harvest.

The results and conclusions yielded by the thesis are based on in-situ measurements of the following data: soil-surface CO_2 flux (R_s), weight loss of needle litter and coarse roots in litterbags, soil temperature and moisture, and assessments of C stocks in soil, ground vegetation and trees as well as percentage area disturbed by the different methods. The results showed that site preparation and stump harvests have no or reducing effects on soil-surface CO_2 flux (R_s), and that any initial increase in R_s is limited to the first few weeks. Removal of the humus layer, thereby exposing the mineral soil, led to lower R_s than in control plots. However, a double humus layer did not result in higher than control R_s values. Thus, R_s seems to be related to the presence of a humus layer rather than its thickness (if present). Mixing the humus layer and mineral soil did not lead to higher R_s than control fluxes, and in one experiment it even led to lower R_s. The location of incubated litter (in bags) strongly influenced the decomposition rate, as buried litter decomposed more rapidly than litter placed on the soil-surface. However, the higher decomposition rates associated with buried litter were not accompanied by increases in R_s from the entire soil profile.

After three decades, the most pronounced effects of site preparation on the entire ecosystem C stocks were increases due to enhancement of the growth of planted trees (*Pinus sylvestris*, *Picea abies* and *Pinus contorta*), relative to control.

General conclusions are that site preparation and stump harvests do not lead to reductions of the soil or ecosystem C stocks, and in the long-term promoting strong growth of forest trees is the most important measure for securing C stocks of entire forest ecosystems, including those of the soil.

Keywords: Forestry, coniferous forest ecosystem, mineral soil, C stock, soil-surface CO_2, litter weight loss, decomposition

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Contents

List of Publications

This thesis is based on the following papers, referred to by Roman numerals in the text:

I Strömgren, M., Mjöfors, K., Holmström, B. & Grelle, A. (2012). Soil CO_2 flux during the first years after stump harvesting in two Swedish forests. *Silva Fennica,* 46**,** 67-79.

II Strömgren, M. & Mjöfors, K. (2012). Soil-CO_2 flux after patch scarification, harrowing and stump harvest in a hemi-boreal forest. *Scandinavian Journal of Forest Research,* 27**,** 754-761.

III Mjöfors, K., Strömgren, M., Nohrstedt H-Ö, Gärdenäs A.I (2015). Impact of site-preparation on soil-surface CO_2 fluxes and litter decomposition in a clear-cut in Sweden. (*Silva Fennica,* In revision)

IV Mjöfors, K., Strömgren, M., Nohrstedt H-Ö, Johansson M-B, Gärdenäs A.I (2015). Indications that site preparation in the long-term increases overall carbon stocks in coniferous boreal forests but not in their soils. (Manuscript)

Papers I-III are reproduced with the permission of the publishers.

The contribution of Kristina Mjöfors to the papers included in this thesis was as follows:

I Shared main authorship. Planned the field experiment together with co-authors. Performed field measurements and field analyses. Performed data analysis. Carried out the writing with the assistance of the co-authors.

II Second author. Planned the field experiment together with first-author. Performed field measurements and field analyses. Performed data analysis. Contributed to writing of the paper.

III Main author. Planned the field experiment together with second-author. Performed field measurements and field analyses. Performed data analysis. Carried out the writing with assistance of the co-authors.

IV Main author. Performed field measurements and field analyses. Performed data analysis. Carried out the writing with assistance of the co-authors.

Abbreviations

C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
CON	Control
DHL	Humus layer overturned on top of the adjacent humus layer
EMS	Exposed mineral soil. No humus layer, mineral soil visible
INT	Intact humus layer, no visible disturbances of the soil-surface.
IRGA	Infrared gas analyser
MIX	Humus layer and mineral soil mixed together
N_2O	Nitrous oxide
R_s	Soil-surface CO_2 flux
SPM	Site preparation method
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

Ongoing increases in global atmospheric carbon dioxide (CO_2) concentrations and other greenhouse gases, primarily driven by anthropogenic use of fossil fuels and land use changes, are causing increasing concern. Thus, a goal enshrined in the Kyoto Protocol (Swedish Environmental and Protection Agency, 2015) is to reverse the increases in man-made greenhouse gas emissions. To restrict increases in average global temperatures to 2 °C or less (a widely accepted 'safe' limit), greenhouse gas emissions must be reduced by at least 50% relative to 1950 levels by 2050 according to the Intergovernmental Panel on Climate Change (IPCC, 2013). Enhancing storage of carbon in boreal forest soils could play an important role in these efforts, because: globally soils store about 1 600 Pg carbon (C), more than twice the amount of C present as CO_2 in the atmosphere; twice as much C is reportedly stored in forest soils than in the tree biomass (Goodale et al., 2002, Raich and Schlesinger, 1992,); and ca. 10% of the earth's total organic C is stored in boreal forest ecosystems (Schlesinger and Bernhardt, 2013). However, to facilitate the mitigation of CO_2 emissions, greater understanding of C cycle processes and pools is needed. Furthermore, Annex 1 Parties to the Framework Convention on Climate Change (which include Sweden) are obliged to report changes in soil C pools, unless they can prove that their soils are not a source of CO_2 emissions to the atmosphere (UNFCCC, 2006). Thus, to ensure that Sweden can fulfil its Kyoto Protocol commitments, and report its greenhouse gas emissions to the United Nations Framework Convention on Climate Change (UNFCCC), both regional and national research has been undertaken since the 1990s to improve estimations of C stocks.

A major way to decrease consumption of fossil fuels, and associated emissions of greenhouse gases, is to replace them with renewable energy sources. Thus, the European Union adopted an integrated energy and climate change policy in 2008, with several targets including increasing the proportion of renewable fuels used in Member States to 20% of the total by 2020 (EU, 2009). This has led to increased interest in identifying and developing reliable renewable resources, *inter alia* using tree stumps for bioenergy purposes (Persson, 2013). The biomass in stumps and coarse roots corresponds to almost half of the stem biomass in a mature coniferous forest (Egnell et al., 2007, cf. Marklund, 1988) and the same proportion is present in branches and tops (Karlsson, 2007). Consequently, substantial amounts of renewable bioenergy could be obtained from stumps, ca. 125 MWh per clear-cut ha on average, but stump extraction causes soil disturbance, which can lead to increases in decomposition of soil organic matter and hence reductions in soil C stocks (e.g. McLaughlin et al., 2000, Lundmark-Thelin & Johansson, 1997, Johansson, 1994). However, these and other environmental consequences of stump harvesting are poorly understood (Persson, 2013, Walmsley & Godbold, 2010, Egnell et al., 2007). Thus, to assess the extent to which stumps can be truly considered a carbon-neutral energy source thorough evaluation of the effects of extracting them on soil carbon pools and fluxes is needed.

Site preparation methods prior to sowing or planting seedlings in commercial plantations also create disturbance, with poorly understood effects on C stocks. Thus, in summary, increasing recognition of the potential utility of using stumps, together with the importance of soil organic C stocks and dynamics for mitigating greenhouse gas emissions has highlighted the need for improved knowledge of the effects of site preparation and stump harvesting on C stocks in the soil and entire forest ecosystems in Sweden. These are the focal topics of this thesis.

2 Aim

The overall aim of the studies, which this thesis is based upon, was to assess changes in soil and vegetation C stocks after common site preparation methods and stump harvesting. The site preparation methods considered include: patch scarification (Papers I, II and III), mounding (Paper IV), harrowing (Papers II, III and IV) and ploughing (Paper IV). These site preparation methods and stump harvesting disturb the soil to varying extents and in different ways, creating different types of disturbance, such as exposed mineral soil or double humus layers, and mixtures of organic matter with mineral soil.

The specific aims of the studies were to assess:

- proportions of clear-felled areas affected by specific classes of disturbance after site preparation and stump harvest (Papers I and II)
- immediate and short-term (two years) responses of soil-surface CO_2 fluxes (R_s) to the considered types of disturbance resulting from applied site preparation and stump harvest treatments (Papers I, II and III)
- potential differences in overall effects of the site preparation and stump harvest practices on R_s (Papers I, II and III)
- the impact of various disturbances related to site preparation on needle and root decomposition (Paper III)
- long-term effects of site preparation methods on C stocks of the forest ecosystem as a whole and its separate parts (Paper IV)

3 Background

3.1 Swedish forests

Sweden is one of the most extensively forested countries in the EU, with 23 Mha of productive forest land, *ca.* 18% of the total forested area in EU27 countries (SLU, 2013, FAO, 2011). Every year, ca. 0.23 Mha is clear-cut and some form of site preparation is applied to 92% of this area (Swedish Forest Agency, 2014) to stimulate re-growth in forest regeneration areas. Due to improvements in forest management practices such as these, the standing tree stock in Swedish forests has increased by 80% since 1920 (Swedish forest Agency, 2011). Swedish forests are dominated by conifers, which comprise about 80% of the total tree population. The most common species are *Picea abies* (L) Karst (44%) and *Pinus sylvestris* L. (39%). The most common deciduous species is *Betula pendula* Roth., comprising ca. 11% of the standing volume. Durations of rotations in commercial conifer plantations vary from 80 to 130 years in the north of Sweden and from 60 to 100 years in the south, depending on the local site fertility (which increases strongly from north to south). Although some forest land is on sedimentary soils (15%), most forests are established on glacial tills (75%) (Swedish Forest Agency, 2014).

Swedish forest soils contain an estimated 1700 Tg of C, which is equivalent to *ca.* 100 times the Swedish annual emissions of greenhouse gases (corresponding to 15 Tg C) (Swedish Environmental and Protection Agency, 2015). Thus, even minor changes in forest soil C storage will strongly influence the Swedish national C budget. These estimates highlight the need for improving knowledge of effects of disturbances following site preparation and stump harvesting on soil C stocks, and better general understanding of the boreal forest C cycle.

3.2 The terrestrial carbon cycle

Generally (during vegetative growth periods) plants fix CO_2 from the atmosphere through photosynthesis, and release some of the fixed carbon back into the atmosphere as CO_2 via autotrophic respiration. In addition, they continually transfer C to the soil organic matter pool by dropping litter, i.e. dead biomass (needles, twigs and fine roots), and eventually all of their biomass is returned to the ecosystem when they die (if they are not harvested). Various decomposer organisms degrade the litter and use the carbon-containing substances in it as sources of energy and carbon skeletons in their metabolic processes, which include release of CO_2 into the atmosphere via heterotrophic respiration. Diverse organisms, including various soil fauna and microbes, are involved in decomposition, rates of which are influenced by numerous environmental factors, including soil temperature, moisture, chemistry, and substrate quality. For instance, decomposition rates of soil organic matter are generally positively correlated with soil temperatures (Ågren and Andersson, 2012, Lloyd and Taylor, 1994), and slow at both low and high moisture contents (Ågren and Andersson, 2012, Orchard and Cook, 1983). The quality of the litter (in terms of carbon:nitrogen ratio and/or lignin content) depends on the plant species from which it originated and amounts of degraded substances (Berg and Laskowski, 2005, Aerts, 1997, Aber et al., 1990). Generally, litter is initially decomposed rapidly, as readily degraded substances are removed, but the residual organic matter becomes increasingly recalcitrant, and increasingly strongly adsorbed to mineral soil particles (Hassink, 1992, Allison et al., 1949). In a forest soil profile, the C contained in organic residues generally becomes older with depth (Rumpel et al., 2002). Fröberg et al. (2011) concluded that, in Scandinavia, the average age of the humus layer is ca. 40 years. However, some parts of the organic substrate are so recalcitrant that it can remain in the mineral soil for thousands of years (Kleber, 2010).

3.3 Site preparation

In Sweden, site preparation has been used as a management practice for several decades in order to improve seedling survival and growth during the regeneration phase. The term pertains to all types of treatments intended to change the environment in order to increase seedling survival and growth rates. Site preparation methods include (*inter alia*) soil scarification, vegetation control with herbicides, and prescribed burning. In this thesis the focus is on mechanical site preparation, in which the surface layers (including the humus layer) at selected areas may be inverted, and placed on adjacent areas, thus exposing some mineral soil. Alternatively, the humus layer may be buried under a raised mineral soil layer, or mixed with the top layer of the mineral soil. Site preparation can be intensified by increasing the treatment depth or the proportion of the area treated. More than 80% of all clear-cuts in Sweden are subjected to some form of site preparation (Swedish Forest Agency, 2014). Between 2000 and 2010, 52% of the site-prepared area was harrowed, 25% was patch scarified and other methods were applied to the rest (Eriksson 2014). The site preparation methods considered in this thesis are:

- Patch scarification and mounding (Fig. 1A): Mineral soil and organic material are inverted and placed on an adjacent area of undisturbed soil, thereby creating a "mound" with a double humus layer below a mineral soil layer. Mounding is a more intense form of patch scarification, the intensity of which is expressed as height of the piles. These methods affect roughly 25% of the soil-surface of clear-felled areas (Bäcke et al., 1986).
- Harrowing (Fig. 1B): Rows of tilts and furrows are created, with the tilts comprising mixed mineral soil and organic matter. The furrows are often shallow (*ca.* 10-20 cm deep). This method affects roughly half of the soil-surface of clear-felled areas (Bäcke et al., 1986).
- Ploughing (Fig. 1C): Several-decimeter deep parallel ditches are formed, resulting in thick rows of mineral soil beside double humus layers. Around 70% of the area is affected. Ploughing is the most intense site preparation method considered here. Moreover, since 1993, it has been forbidden in Sweden, due to its heavy impact on the soil.

Sutton (1993) and Örlander et al. (1990) have earlier described mechanical site preparation methods in greater detail.

Figure 1. A-D. Photographs showing effects of the site preparation methods — mounding (A), harrowing (B) and ploughing (C) — discussed in this thesis and stump harvesting (D). Photographs A-C by Åke Nilsson, and D by Bengt Olsson.

Site preparation is applied to optimize physical and biological conditions for planted seedlings during their establishment. Several studies have confirmed that site preparation increases survival rates after plantation or sowing on most sites (Johansson et al., 2013, Nordborg et al., 2003, Archibold et al., 2000, Örlander et al., 1998, Kubin and Kemppainen, 1994,), possibly through the following mechanisms.

i) Removal of competing field-layer vegetation. When a mature forest is harvested the resulting clear-cut generally has a sparse field vegetation layer. The upcoming field vegetation competes with planted seedlings for resources, such as nutrients, water and light (Imo and Timmer, 1999, Nilsson and Örlander, 1999, Malik and Timmer, 1996, Nambiar and Sands, 1993,).

ii) Avoidance or reduction of pine weevil attacks (Nordlander et al., 2011, Örlander and Nilsson, 1999). In southern Sweden, pine weevils can cause severe damage to planted seedlings during the first three years following clear-cutting. However, creating an area of bare mineral soil around seedlings deters their attacks.

iii) Promotion of nutrient release from organic material by stimulating microbial activity (Pumpanen et al., 2004, Nordborg et al., 2003, Lundmark-Thelin and Johansson, 1997, Johansson, 1994)

iv) Increase in soil temperature through the changes in elevation created by mounds and tilts (Devine and Harrington, 2007, Örlander et al., 1998, Örlander et al., 1990). Frost damage can be mortal for the planted seedlings, and the creation of a bare mineral soil area close to the seedling can prevent this adverse effect (Langvall et al., 2001). Raising the soil temperature also stimulates root growth, water uptake by roots through associated reductions in viscosity and increases in root permeability (Iivonen et al., 1999, Cooper, 1973), and increases both the release and uptake of nutrients (Mellander et al., 2008, Mellander et al., 2004, Gessler et al., 1998, Ross and Malcolm, 1982, Bowen, 1970).

v) Improvement of soil moisture content and aeration in relation to seedlings' needs. When the mineral soil is mixed with the organic material the soil moisture content changes in the top 10 cm layer: falling in the mound and tilts, but rising in the furrows (Sutinen et al., 2006, MacKenzie et al., 2005, Mäkitalo and Hyvönen, 2004, Burton et al., 2000, Elliott et al., 1998, Örlander et al., 1998, Örlander et al., 1990).

3.4 Stump harvests

Stumps are harvested (Fig. 1D) by removing them using a device such as an excavator with a "Pallari" stump-head, which can simultaneously lift and split them. Stumps are generally first lifted and shaken to remove as much soil as possible, then split into halves and left to dry in small heaps on the clear-felled area. However, larger stumps are split before lifting. Stump harvesting is currently a common practice in Finland, where it is annually applied on areas covering 20 000 ha on average (Juntunen, 2011).

During 2011-2013, the stump harvesting area was restricted to 2 500 ha yr^{-1} in total for Swedish forest owners certified by the Forest Stewardship Council (FSC). According to the Swedish Forest Agency (2009) stumps could be harvested on about 10 000-20 000 ha annually, corresponding to ca. 5-10% of the clear-felled area. However, as this is a relatively new approach, there is limited information regarding its possible environmental impact (Persson, 2013). Stump harvesting leads to more pronounced disturbance than the common site preparation methods and affects 70% of the treated area (Kataja-Aho et al., 2011).

3.5 Effects of site preparation and stump harvest on soil C stocks

The changes in soil temperature and moisture caused by site preparation when the humus layer is buried in or mixed with mineral soil may be favorable for decomposers (Fleming et al. 1994, Johansson 1994, Örlander et al., 1990). This may lead to increased fluxes of soil-surface CO_2 (R_s) into the atmosphere and hence losses of soil C stocks. On the other hand, site preparation promotes establishment and growth of new tree seedlings (e.g., Johansson et al., 2013, Örlander et al., 1998,), thereby increasing fixation of CO_2 from the atmosphere through photosynthesis, and hence increasing ecosystem C stocks. Associated subsequent increases in inputs of root and needle litter to the soil may also increase soil C stocks. Rises in carbohydrate fluxes from green photosynthesizing leaves to roots also promote the growth of mycorrhizal mycelia (Nehls, 2008).

Since soil C stocks are so extensive and heterogeneous, relatively small changes in them induced by site preparation and stump harvests may be difficult to detect, especially if assessments are based on soil core sampling (Muukkonen et al., 2009). Short-term changes in the stocks (which can have major cumulative effects, even if they seem small) can be detected by measuring net fluxes of CO_2. Few studies have measured CO_2 emissions *in situ* after site preparation or stump harvests, but Pumpanen et al. (2004) found that site preparation had substantial effects on soil-surface CO_2 flux (R_s). They reported that fluxes were lowest from microsites/spots where the organic matter had been removed, and highest at microsites with a double humus layer. Mallik and Hu (1997) also found that mixing the soil down to 20 cm depth on a clear-cut increased the R_s, relative to fluxes from undisturbed control plots, but more recently Uri et al. (2015) detected no differences in R_s between a stump-harvested clear-cut and an untreated clear-cut.

Another method that can be used to study decomposition of organic material *in situ* is the litterbag technique (Johansson 1994, Singh and Gupta 1977), in which organic materials (usually needles, leaves or roots) are incubated in terylene bags in the field, normally on the soil-surface or at selected depths. Litterbags are repeatedly sampled, allowing losses in mass to be monitored over time. Lundmark-Thelin and Johansson (1997) and Johansson (1994) both found that decomposition of buried needle litter increased in site-prepared areas.

It is widely believed internationally, as outlined in several reviews, that site preparation leads to a long-term reduction in soil C stocks (Jandl et al., 2007, Freeman et al., 2005, de Wit and Kvindesland, 1999, Johnson, 1992). However, the sources of data in these reviews are studies on site preparation methods that are not normally applied in Sweden, with just two exceptions. In these exceptions, Nordborg et al. (2006) found no difference in soil C stocks between plots subjected to ploughing and patch scarification 10 years after treatment. In contrast, Örlander et al. (1996) found that C stocks were 6-41% lower in scarified plots than in untreated controls up to 70 years after treatment (mainly due to losses in the organic layer) at five sites in Sweden, but the treatments applied are no longer used in forestry and the experimental design did not allow rigorous statistical analysis. A more recent study (Egnell et al., 2015) detected no significant differences in soil C stocks between plots subjected to ploughing combined with stump harvest and plots with light, manual patch scarification.

Several studies have also examined effects of stump harvest on soil C stocks. Strömgren et al. (2013) found that stump harvesting had resulted in lower C stocks in the humus layer, but no differences in total soil C stocks, relative to harvesting only stems, 25 years after treatment. Karlsson and Tamminen (2013) found that stump harvest had little or no effects on soil C stocks in the humus layer or top 10 cm of the mineral soil, 33 years after treatment. Similarly, Egnell et al. (2015) noted no differences in soil C stocks between plots subjected to stump harvesting combined with deep soil cultivation and plots with manual patch scarification, two decades after treatment.

Clearly, to obtain a complete understanding of the effects of using stumps as a source of energy on the overall C budget, reductions in the C pool stored in stumps and coarse roots in the forest should also be considered. With stump harvesting, the CO_2 that would have been emitted slowly from a decaying stump pool in the forest will instead be emitted by combustion about one or two years after the harvest. Swedish forests stumps reportedly lose half of their mass in about 14 years (Palviainen et al., 2010, Melin et al., 2009). Since this pool decreases with time, the temporal perspective is important when assessing the effect of using stumps for bioenergy in mitigating climate change. There are also other factors that have to be taken into account, such as the energy required for harvesting, transporting and preparing the stumps for their final use. Nevertheless, following a life-cycle assessment of stump harvesting, Lindholm (2010) concluded that great savings in greenhouse gas emissions could be obtained by substituting fossil fuel with stumps. Moreover, the longer the time perspective is, the greater the potential savings are.

3.6 Hypotheses

The above review shows that stump harvesting, and site preparation, may have highly complex and incompletely understood effects on C stocks. Therefore, in efforts to improve understanding of how ecosystem C stocks are affected by several site preparation methods and stump harvesting, the following hypotheses have been tested in the studies this thesis is based upon.

- Hypothesis I (addressed in Papers I, II and III): R_s is controlled by the amount of organic matter in the soil. Thus, if the humus layer is removed CO_2 emissions are likely to fall, due to the lack of substrate for decomposers, while doubling the amount of organic material per unit surface area by adding an extra humus layer should substantially increase the R_s.

- Hypothesis II (addressed in Papers I, II and III): Mixing mineral soil and humus-layer material increases the R_s by enhancing conditions for microbial activity, thereby increasing decomposition rates and R_s.

- Hypothesis III (addressed in Papers I, II, III and IV): The larger the proportion of the area affected by disturbance, the higher the R_s will be. Disturbance of the soil-surface is expected to increase the decomposition of organic matter, resulting in higher R_s, and lower soil C stocks in the long-term.

- Hypothesis IV (addressed in Paper IV): The C stocks in vegetation (above- and below-ground) increase with the intensity of site preparation. The increase in vegetation C stock is expected to compensate for the expected loss in soil C stocks, thereby leading to a higher C stock in the whole ecosystem in site-prepared areas. This effect is likely to be long-term.

4 Materials and methods

4.1 Site description and experimental design

To test the hypotheses and meet the aims of the studies, three stump harvest experiments were established, each at one of three sites (Stadra, Karlsheda and Fågelfors). These sites were selected because they were deemed to have representative conditions for stump-harvesting sites and were planned to be stump-harvested reasonably soon by practical forestry. An additional experiment was established at another site (Åmot) to study effects of different types of soil disturbance that are commonly caused by site preparation and stump harvest. This site was chosen because its soil was glacial sand, so the disturbances of each class would be more homogeneous than at an otherwise similar site with a till soil. To assess the long-term consequences, site preparation experiments on two sites established in the early 1980s were used. In total, six sites were included in the studies behind the thesis. All these experimental sites have podzolic soils, of "moist" or "mesic" soil moisture classes, and were established in clear-cuts of former coniferous stands. The sites are spread along a climatic gradient, with mean annual temperature and precipitation declining to the north. The locations and characteristics of the sites are presented in Fig. 2 and Table 1. The experimental design is described below, while more details of the applied methods can be found in section 3.2.

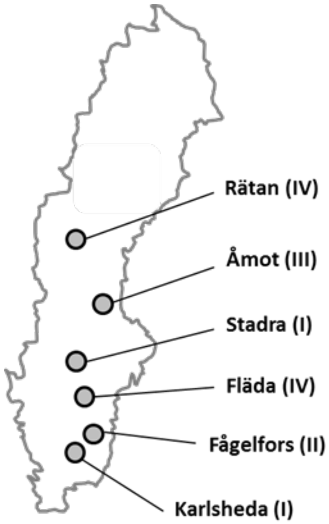

Figure 2. Locations and names of the six sites used in studies reported in papers indicated by the numbers in parentheses.

4.1.1 Stadra (Paper I)

Stadra is situated in central Sweden (N59°56′ E14°73′), close to Nora municipality (Fig. 2). Before clear-cutting, the site supported a stand of *P. abies*. It is quite productive (G100 = 30, where G100 is the estimated height of the tallest trees, in m, at 100 years of age) and the soil type is a podzol formed on a loamy till. Further details of this and the other sites' environmental characteristics and forest management history are presented in Table 1.

At Stadra, effects of patch scarification and stump harvesting, using an excavator equipped with a "Pallari" stump-head (which can both harvest stumps and create mounds), were compared. On the clear-felled area, 50×50 m plots were distributed in a randomized block design. Each treatment (patch scarification or stump harvest) was replicated three times (one replicate per block). Measured variables included respiration from the soil-surface (monitored using a portable soil respiration system), soil temperature and soil moisture (see sections 4.2.2 and 4.2.3). On one stump-harvested plot an eddy-covariance system was installed. Twenty PVC collars were installed in each plot, for measuring respiration, in a systematic grid with 10 m spacing. Once inserted, the collars were left *in situ* in the field throughout the year, except during the harvesting of the stumps and when the stumps were removed from the clear-cut after drying. After these activities, the collars were re-installed, in approximately the same locations. Three pre-treatment measurements, were made at monthly intervals on the clear-cut before the stump harvesting and patch scarification treatments (in September 2007). After the treatments measurements were made with the portable respiration system on 10 occasions during the growing seasons from October 2007 to June 2009, approximately monthly. The eddy-covariance system was used between June 2007 and October 2009. The position of each collar (and thus measuring point) was assigned to one of the following disturbance classes: intact soil (INT), exposed mineral soil (EMS), a double humus layer (DHL) or mixed humus layer and mineral soil (MIX).

4.1.2 Karlsheda (Paper I)

Karlsheda (Fig. 2) is situated in southern Sweden (N57°13' E15°50'). The former forest stand consisted of *P. abies*, and the site index was H100=28. The soil type is podzol, and parent material is sandy-loamy till (see Table 1 for further site details).

The Karlsheda field experiment was a short-term (one month) study, in which R_s was compared in three 50×50 m plots in a stump-harvested clear-cut and two plots in an untreated clear-cut before and after the stump-harvesting (for which an excavator equipped with a "Pallari" stump-head was again used). In each plot, 20 PVC collars were installed in a systematic grid with 10 m spacing for the measurements.

Pre-treatment measurements of R_s, soil temperature and soil moisture were made a week before the stump harvest, and six further measurements during the month following the treatment. Each measurement point in the stump-harvested plots was assigned to one of the disturbance classes described above (INT, EMS, DHL or MIX).

4.1.3 Fågelfors (Paper II)

The Fågelfors site is a 10 ha clear-felled area in southern Sweden (N57°13' E15°50'; Fig. 2). The former stand was dominated by *P. abies*, with a smaller proportion (20%) of *P. sylvestris*. The soil type is a podzol that has evolved on a sandy-loamy till (see Table 1 for further site characteristics).

On the clear-cut area, nine 30×30 m plots were distributed and triplicates were subjected to three treatments (patch scarification, harrowing and stump harvest). As 30×30 m plots were too small for the mechanical harrowing, these three plots were situated in a separate part of the designated area. The plots designated for stump harvest and patch scarification were chosen randomly. In each plot, measurements were performed using 16 PVC collars placed in a systematic grid (5 m apart), and four additional PVC collars per plot placed in areas of underrepresented soil disturbance classes (thus there were 20 sampling points per plot). Once again, an excavator equipped with a "Pallari" stump-head was used for the stump harvest and patch scarification, while a forwarder equipped with a disc trencher was used for harrowing. No measurements were acquired before the site preparation and stump harvest were performed, in September 2009, but R_s, soil temperature and soil moisture were measured on five subsequent occasions between April and October in both 2010 and 2011 (10 occasions in total).

4.1.4 Åmot (Paper III)

The Åmot site (Fig. 2) is situated in central Sweden (N60°59', E 16°24'). The soil parent material is glacial sand and the soil type is a podzol. Before the final harvest, performed in May 2009, the forest stand contained 50% *P. sylvestris* and 50% *P. abies*. For further details, see Table 1.

At the site an experiment was established on a clear-cut, in which areas with INT, EMS, DHL and MIX disturbances (as described above) were created in 2×2 m plots with four replicates, on 16 June 2009 using an excavator equipped with a backhoe. The purpose of this experiment was to imitate and characterize in detail the micro-environments (small-scale conditions) that are commonly created following site preparation and stump harvests.

In each plot, four PVC collars were installed for measurements. Initially, R_s and micro-climatic measurements were taken just before the treatments in June 2009. The collars were replaced directly after the treatments, and left in the ground during the rest of the study. To avoid differences in R_s due to diurnal variation, the 16 plots were divided into four blocks, and R_s measurements were performed within one hour in each block. After the treatments, measurements were acquired on 10 occasions starting 5 days after the treatments and usually 2-3 weeks apart thereafter, from late June to early October in 2009. In 2010, five measurements were conducted, from mid-May to mid-October. Field vegetation was absent or negligible during the first year following the disturbance, but grass (mainly *Deschampsia flexuosa*) started to grow on the plots in the second year and reached ca 10 cm in height by the end of the second vegetation period.

Sets of 25 litterbags (see section 4.2.5) containing needle litter and 30 containing coarse roots were placed in each plot on 16 June 2009, directly after the treatments. Five litterbags with needle litter and five with root litter were retrieved from each plot every spring (May) and autumn (Sept-Oct), during the 2009-2011 measurement periods, and the remaining root litterbags were collected in October 2012.

4.1.5 Fläda (Paper IV)

Fläda is located in southern Sweden (N58°41′ E15°02′) on a podzolic stony, sandy sediment (see Table 1 for further site details). At this site *P. sylvestris* and *P. abies* were planted in experiments with a randomized block design. In both cases, there were four 30×30 m plots replicated in each of two blocks in the same clear-cut area. In each block three site preparation methods (mounding, harrowing, and ploughing) were each applied together with a control. The previous stand (50% *P. sylvestris* and 50% *P. abies*) was felled in 1982 and 1983. The site preparation methods were applied in 1984 and seedlings were planted in the following year. In 2009, the site was re-visited to evaluate long-term effects of the treatments on the total ecosystem C pool. Eighteen soil samples and ground vegetation samples were taken randomly along a diagonal transect at each plot. In the ploughed plots, more samples (36) were taken to cover the high spatial heterogeneity that this site preparation method caused. All trees in the plots were measured, and total ecosystem C stock for each treatment was estimated by summing estimated stocks in the soil, ground vegetation and trees.

4.1.6 Rätan (Paper IV)

Rätan is located in the western part of central Sweden (N62°30′, E14°36′). The former stand was a mixture of *P. sylvestris* (78%), *P. abies* (20%) and *B. pendula* (2%). The soil is a podzolic sandy-silty till (again see Table 1 for further site details). The experimental design and sampling methods used in the study at this site were the same as those applied at the Fläda site (see section 4.1.5), except that *Pinus contorta* Dougl. var. *latifolia* Engelm. seedlings were planted. The site preparation methods were applied in 1981, a year after final felling of the previous stand. The soil and ground vegetation were sampled in 2007 and the tree biomass was estimated in 2009.

Table 1. *Descriptions of the six sites used in the studies this thesis is based upon, as reported in Papers I-IV.* [1]*IUSS (2007),* [2]*Soil moisture classes according to MarkInfo, www-markinfo.slu.se,* [3]*Height of the two tallest trees, m, at 100 years.* [4]*Climate refers to means for 1961–1990, obtained from official statistics (SMHI 2015).*

	Karlsheda	Stadra	Fågelfors	Åmot	Fläda	Rätan
Site information	*Paper I*	*Paper I*	*Paper II*	*Paper III*	*Paper IV*	*Paper IV*
Coordinates	N 57°53’ E 15° 08’	N59°46’ E14° 74’	N57°13’ E15° 50’	N60° 59', E 16° 24'	N58°41´ E15°02´	62°30´14°36´
Soil texture and parent material	Sandy-loamy till	Loamy till	Sandy-loamy till	Glacial sand	Stony, sandy sediment	Sandy-loamy till
Soil type[1]	Podzol	Podzol	Podzol	Podzol	Podzol	Podzol
Soil moisture[2]	Mesic	Moist	Mesic-Moist	Mesic	Mesic	Mesic
Site index (H100)[3]	28	30	28	26	28	20
Mean annual air temperature (°C)[4]	5.5	4	5.5	4.3	5.2	2.2
Annual precipitation (mm yr^{-1})[4]	700	700	700	600	700	600
Snow cover period[4]	Dec - April	Dec - April	Dec - April	Nov- April	Dec - April	Nov - May
Forest Management History						
Final harvest	Fall 2007	Spring 2007	June 2009	May 2009	1982/1983	1980
Experimental manipulation date	May 2008	Sep-Oct 2007	Sept 2009	Mid-June 2009	1984	1981
Experimental treatments	Control Stump harvest	Patch scarification Stump harvest	Harrowing Patch scarification Stump harvest	Control Exposed mineral soil Double humus layer Mixed soil	Control Mounding Harrowing Ploughing	Control Mounding Harrowing Ploughing
Field measurements	Soil CO_2 flux Soil temperature Soil moisture Area of disturbance	Soil CO_2 flux Soil temperature Soil moisture Area of disturbance	Soil CO_2 flux Soil temperature Soil moisture Area of disturbance	Soil CO_2 flux Soil temperature Soil moisture Needle and coarse root decomposition	C stocks in soil, ground vegetation and tree biomass	C stocks in soil, ground vegetation and tree biomass

4.2 Methods

4.2.1 Estimation of area affected (Papers I and II)

The type of soil disturbance was classified by eye at each R_s sampling point (within the PVC collars). In addition, at the Stadra and Fågelfors sites, the soil disturbance was surveyed along the two diagonal transects in each plot. In every plot, the disturbance at 50 points evenly distributed along each transect was classified in one of five classes, defined as follows:

- INT − Intact humus layer, no visible disturbance of the soil-surface
- EMS − No humus layer, mineral soil visible
- MIX − Humus layer and mineral soil (5-30 cm deep) mixed together
- DHL − Humus layer overturned and placed on the humus layer at an adjacent spot, forming a double layer
- Wheel-ruts − Clearly visible wheel-ruts

4.2.2 Soil-surface CO_2 flux (Papers I, II and III)

R_s was measured with a portable soil-respiration system, consisting of an infra-red gas analyzer (IRGA) connected to an opaque soil-respiration chamber (EGM-4 with a SRC-1, PP-systems, Hitchin, UK), according to Parkinson (1981). The IRGA was equipped with a humidity sensor and a pressure sensor that automatically corrected the CO_2 concentration measurements to account for variations in humidity and air pressure. During measurements, the respiration chamber was attached to a pre-installed collar (10 cm in diameter). Measurements were acquired every 4.2 seconds during an 80 second-long incubation period. The last 14 measurements were used for estimating R_s by linear regression.

PVC collars were inserted about 1 cm into the mineral soil to keep them steady and in close contact with the ground. The height of the collars (and thus their volume) depended on the thickness of the humus layer. The collars were left *in situ* in the field throughout the entire study period, except during site preparation or stump harvest treatments. After these events, the collars were re-installed in approximately the same locations.

After field measurements, the R_s values were corrected to account for the differences in the chambers' volume arising from the variation in height of the collars. If the R_s values did not meet the normal distribution (residuals) and equal variance criteria for statistical analysis, they were log-transformed.

4.2.3 Soil temperature and moisture (Papers I, II and III)

At the same time as each R_s measurement, the soil temperature at 10 cm depth, and the soil moisture at 5 cm depth were measured at a point adjacent to each collar. Soil temperature was recorded with a temperature sensor (STP-1, PP-systems, Hitchin, UK) connected to the portable soil respiration system, and soil moisture with a ThetaProbe (ML2x, Delta-T, Cambridge, UK) using the default settings for mineral soil. The generalized calibration settings for mineral soil, e.g., soils with C content below 7% and a bulk density above 1 g cm^{-3}, were used for the soil moisture sensor. However, since C content and bulk density in the upper 5 cm layer varied among the treatments, soil moisture was only used to indicate differences between dates within treatments, rather than among the treatments.

4.2.4 Eddy-covariance measurements (Paper I)

Ecosystem CO_2 fluxes were measured continuously by eddy-covariance in a stump-harvested plot at the Stadra site. The measurement system consisted of a 3-dimensional CSAT-3 sonic anemometer (Campbell Scientific, Logan, Utah, USA) and an LI-7500 open-path IRGA (LI-COR, Lincoln, Nebraska, USA), mounted 2.2 m above the surface of the stump-harvested area. For further details, see Paper I.

4.2.5 Litterbag method (Paper III)

The decomposition rates of brown needle litter and fresh roots from *P. sylvestris* trees were studied using the litterbag technique, according to Johansson (1994b). Needle litter was sampled from trees in a nearby forest (at Jädraås, 15 km away from the Åmot study site) during the annual litter fall in the autumn of 2006. The *P. sylvestris* root samples were collected in spring 2009, in a forest close to Uppsala (N59°49', E17°40'), 140 km southeast of the study site, by digging down to the root system and cutting roots, approximately 6 mm in diameter, into 6-7 cm long pieces. The needles and roots were dried at room temperature to moisture contents of 5.7 ± 0.5% and 9.8 ± 0.5% (mean and standard error, n=10), respectively. The dry mass of the needles and roots were determined by drying sub-samples at 85 ºC for 48 hours then weighing. Approximately 1.5 g samples of needles or roots were enclosed in 11×13 cm litterbags, with 1×1 mm mesh, made of terylene net. The exact weight, expressed in grams to four decimals, was noted on a plastic strip that was also enclosed in the bag.

In areas representing the INT disturbance class, needle litter was placed on the soil-surface, while root litter was inserted at 5 cm depth. In areas representing the other disturbance classes, the litterbags were placed in positions where the site preparation was presumed to have moved the root and needle litter: on the surface of EMS areas, between the two humus layers of DHL areas, and in the mixed layer of MIX areas (Fig. 3). The litterbags placed on the soil-surface were fastened to the ground with 5 cm long metal pins at the start of the experiment, while twine was attached to those buried in the soil to facilitate collection.

After placing the litterbags in the field, subsets were collected at six-month intervals. The collected litterbags were cleaned of soil particles, mosses, lichen, grass, and dwarf shrubs. The remaining dry weight of litter in each bag was determined after drying for 48 hours at 85 °C.

The replicated litter samples collected on each occasion were pooled to obtain a composite needle sample and a composite root sample for each plot. These samples were subsequently ground and their C contents were analyzed following Ohlsson and Wallmark (1999), using a DeltaV Isotope ratio Mass Spectrometer coupled to a Flash 2000 elemental analyzer (both supplied by Thermo Fisher Scientific).

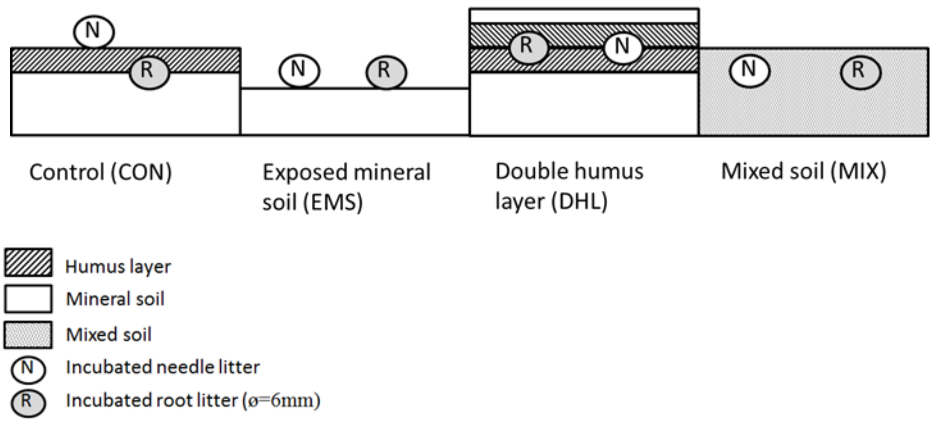

Figure 3. *Schematic diagram of the disturbance classes — control (INT), exposed mineral soil (EMS), double humus layer (DHL), and mixed humus and mineral soil (MIX) — and locations of the incubated litterbags containing needle (N) or root (R) litter.*

4.2.6 Mineral soil and humus layer sampling (Paper IV)

Soil was sampled by collecting cores with a 5 cm diameter probe (Fig. 4), down to 30 cm depth. The humus layer was sampled at the same point, either integrated in the soil core (Rätan site), or separately with a sharp-edged steel cylinder (ø = 100 mm, Fläda site). If the soil probe could not reach sufficient depth due to rocks, logs or roots of living trees, another sample was taken in close proximity to the initial point. The embedded humus layer in samples with a double humus layer was classified as mineral soil. The samples were frozen until preparation for chemical analyses, when they were first defrosted and then sieved through a 2 mm (mineral soil) or 6 mm (humus layer) mesh to remove gravel and roots and to homogenize the samples. They were subsequently dried at 105 ºC for 24 h. C and N contents in the samples from the Rätan site were determined using an elemental analyzer (LECO CNS-1000, St. Joseph, USA), while an inductive plasma spectrometer (ICP Optima 3000 DV, Perkin Elmer, USA) was used for samples from the Fläda site. Next, the weight of the mineral soil (< 2 mm particles) and the humus layer from the cores was multiplied by the C and N percentages to obtain the respective contents. A correction for the stoniness (> 2 mm) was also applied, based on measurements with the surface penetration method (Viro, 1952).

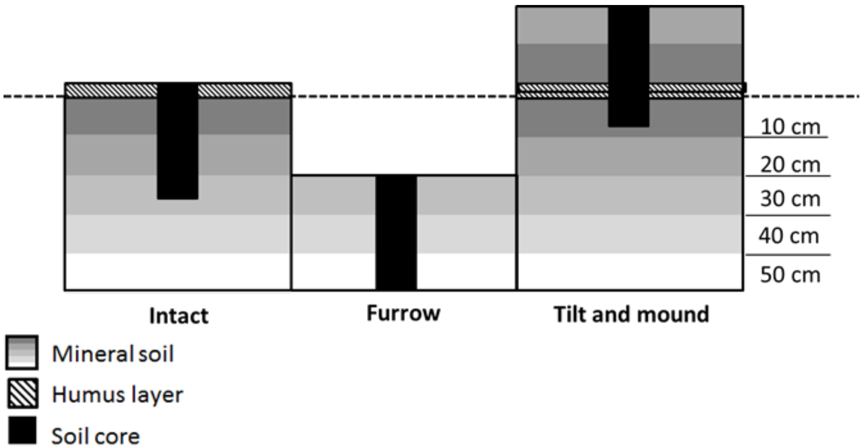

Figure 4. Schematic representation of the manner in which soil samples were obtained from indicated areas of site-prepared plots. The dotted line represents the surface of the intact mineral soil. The Furrow shows the exposed mineral soil remaining after removal of soil to form a mound or tilt. The Tilt and mound shows the inversion of the humus layer and top layer of mineral soil and placement on an adjacent intact soil-surface, creating an area with a double humus layer covered by mineral soil.

4.2.7 Estimation of ground vegetation and tree C stocks (Paper IV)

Samples of mosses and field vegetation were collected by removing the entire layer in 25×25 cm areas. The vegetation was subsequently dried (at 75 °C for 48 hr) and weighed. The C content in the biomass of mosses and field vegetation was assumed to be 50% of dry weight (Lamlom and Savidge, 2003).

In all three of the experiments (at Fläda and Rätan) conifer species regarded as suitable for the site conditions had been planted. To estimate their biomass, all trees were calipered at breast height (1.3 m), and their height was measured in 2009. To calculate stem volumes of *P. sylvestris, P. abies*, and *B. pendula* trees with diameter at breast height (dbh) >45 mm and thinner trees, functions presented by Brandel (1990) and Andersson (1954) were used, respectively. The stem volume of *P. contorta* trees was calculated using a function presented by Eriksson (1973). Total tree biomass was calculated by multiplying the estimated stem volumes by factors derived from allometric functions established by Marklund (1988) for branches and needles, and Petersson and Ståhl (2006) for stump and root (Ø > 5 mm) systems. The expansion factors, from stem volume (m^3 on bark) to whole tree biomass, obtained using these functions for *P. abies*, *P. sylvestris* and *B. pendula* were 2.77, 2.04 and 1.79, respectively. For corresponding estimates of *P. contorta* biomass, allometric functions presented by Egnell et al. (2015) were used to calculate an expansion factor (1.98) from stem volume (m^3 on bark) to whole tree biomass. To convert whole tree biomass estimates to amounts of C it was assumed that 1 m^3 dry weight of *P. sylvestris*, *P. contorta*, *P. abies* and *B. pendula* respectively weigh 420, 410, 410 and 450 kg (with 30% moisture content; Skogssverige, 2014), and that in each case C accounts for 50% of the dry weight (Lamlom and Savidge, 2003).

4.2.8 Statistical analyses (Papers I, II, II and IV)

Generally, effects of disturbance class or site preparation methods and stump harvest were tested by two-factor analysis of variance (ANOVA), using the procedure “Proc mixed” in SAS Statistical software (V9.3, SAS Institute, Cary, NC, USA) to fit the models. All the response variables except R_s met normal distribution (residuals) and equal variances requirements for ANOVA (for all groups). The lack of homogeneity of variance in the R_s data was overcome by log transformation. Models were run using both data collected in specific years and data collected in all years during the experiments. If a fixed effect was significant, a paired t-test adjusted for multiple comparisons (Tukey-Kramer’s method), was used to identify the differences among disturbance class or site preparation methods and stump harvest. Differences were considered significant if $p \leq 0.05$. More details regarding statistical analyses performed in each of the studies are given in Papers I-IV.

5 Results and discussion

5.1 Area of disturbance (Papers I and II)

The proportion of the soil-surface area affected by the site preparation and stump harvesting varied, depending on the methods used. The proportion of the total area affected by soil disturbance was greatest after stump harvesting at three sites (Stadra, Karlsheda and Fågelfors), where it disturbed up to 70% of the soil-surface (Fig. 5). In places where stumps were removed, mineral soil was exposed (EMS) and a mixture of humus-layer material and mineral soil (MIX) was scattered around. In the stump-harvested areas, the soil disturbance classes MIX and EMS accounted for 51% and 18% of the area, respectively (Fig. 5). Harrowing (at Fågelfors) disturbed 60% of the soil-surface area (Fig. 5), leaving intact areas between long rows of tilt and furrows, classified as MIX and EMS, covering 38 and 22% of the area, respectively (Fig. 5). The least severe treatment was patch scarification (at Stadra and Fågelfors), which only disturbed *ca.* 30% of the soil-surface (Fig. 5), in the form of mounds with double humus layers (DHL) next to pits of EMS. Patch scarification generated similar areal proportions of DHL and EMS in the disturbed areas (Fig. 5). The proportions of disturbed soil were similar to those reportedly created by similar management practices in other studies in Sweden and Finland (Kataja-aho et al., 2011, Lundmark, 1988, Kardell, 1996, 1993, 1992,).

At Stadra there were numerous wheel-ruts and they affected twice as much of the area in the stump-harvested plots than in the patch scarified plots (30% and 15%, respectively). Several factors probably contributed to this. Removal of stumps and associated coarse roots probably reduced the bearing capacity of the soil. The winter before the final harvest was unusually mild, and rainfall was high during the following summer, so the ground was very moist both during final harvest and during the site preparation and stump harvest treatments. In addition, the soil texture in Stadra was finer than at the other sites.

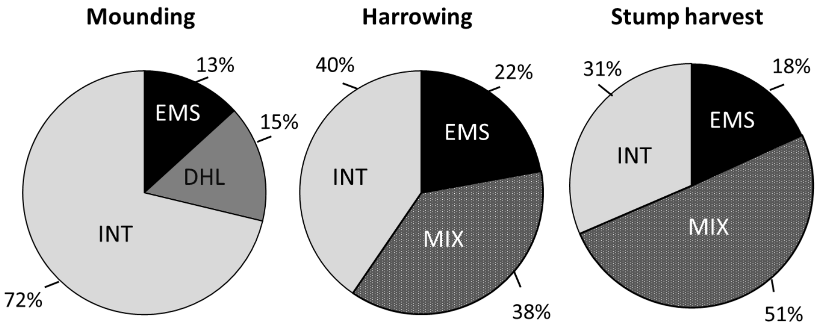

Figure 5. Areal proportions of indicated soil-disturbance classes after mounding, harrowing, and stump harvesting. EMS- exposed mineral soil, DHL- double humus layer, MIX- mixed humus layer and mineral soil and INT- intact soil. Areas of wheel-ruts are not included, but were found to cover 30% of stump-harvested areas and 15% of mounding areas at Stadra.

All these factors made the soil particularly vulnerable to rutting. At Karlsheda there were no wheel-ruts, possibly at least partly because forest residues were left on the site, and branches were laid on the strip road to prevent soil damage. At Fågelfors, wheel-ruts were observed in plots subjected to all treatments, but the ruts were not deep and did not cause any severe disturbance. At both Stadra and Fågelfors sites, the branches and tops were removed, and thus could not be used to increase the soil's bearing capacity, making these sites more vulnerable to rutting.

5.2 Soil-surface CO_2 flux (R_s) after site preparation and stump harvest (Papers I, II and III)

There were no significant differences in pre-treatment R_s measurements across plots within the Stadra, Karlsheda or Åmot sites. Moreover, all the pre-treatment measurements were in the same range as other reported R_s from clear-cuts (Uri et al., 2015, Pumpanen et al., 2004, Mallik and Hu, 1997).

5.2.1 Responses of R_s from different disturbance classes during the first month (Paper I)

In Karlsheda, the R_s values from areas assigned to the four stump harvest soil disturbance classes (INT, EMS, DHL, MIX) were compared to fluxes from undisturbed control (CON) plots. The DHL disturbance class was only represented by six measurement points at Karlsheda, and none at the other stump-harvested sites. The results showed that despite the lack of visible disturbance, R_s was higher from INT areas in the stump-harvested plots than in the CON plots two weeks after the treatment (Fig. 6). This may have been due to disturbance of the soil under the surface by, for example, fine roots being pulled and/or snapped off when the stumps were harvested. However, this difference was small or absent in the later part of June, three weeks after the stump harvest. On the stump-harvested plots, there was no significant difference in R_s between the MIX and INT disturbance areas (Fig. 6). The R_s values were lowest in the EMS areas, and twice as high in DHL areas as in INT areas, on average (Fig. 6). Thus, the month-long study in Karlsheda corroborated Hypothesis I, that R_s is controlled by the amount of available organic matter.

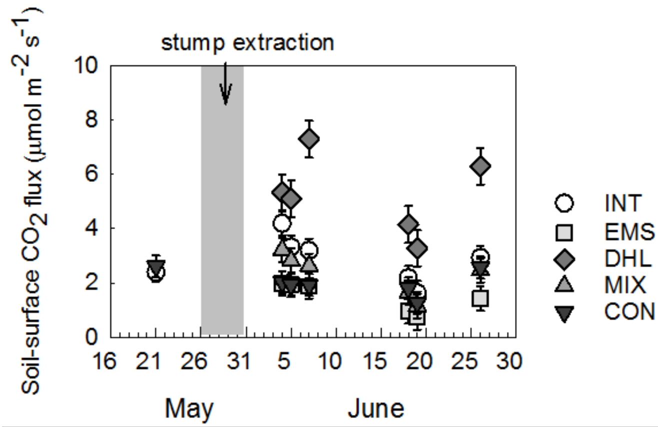

Figure 6. Soil-surface CO_2 fluxes measured in areas of Stump-harvested plots assigned to indicated soil disturbance classes (INT-intact, EMS-exposed mineral soil, MIX- mixed humus and mineral soil and DHL- double humus layer) and undisturbed soil (CON) at Karlsheda, South Sweden, in 2008. Error bars show standard errors.

5.2.2 Responses of R_s during the first two years following the treatments (Papers I, II and III)

At Fågelfors and Åmot the lowest R_s values were associated with the EMS disturbance class during both years (Fig. 7). Similar results have also been reported in other studies (Pumpanen et al., 2004, Mallik and Hu, 1997). However, at Stadra (Fig. 7) the R_s values recorded in EMS areas and areas assigned to other disturbance classes did not differ significantly. Here, values were lower in wheel-ruts (1.4 µmol m^{-2} s^{-1}) than in INT and MIX areas (1.7 and 1.6 µmol m^{-2} s^{-1}, respectively). The indications that R_s was low in EMS areas partially confirmed hypothesis I, that R_s is controlled by the amount of available organic matter. However, this hypothesis implies that R_s should increase when additional humus is added, due to the increased amount of organic matter. This clearly conflicts with findings that R_s was higher from DHL areas than from INT areas at both Stadra and Fågelfors sites, and did not significantly differ between areas assigned to these disturbance classes at Åmot (Fig. 7). Thus, hypothesis I, was rejected, since there was no evidence that R_s was higher in DHL areas than in INT areas at any of the examined sites.

At Åmot, R_s values fluctuated in DHL areas, especially during the first year after treatment: ranging from a third to three times the values recorded in INT areas (Fig. 7). The dates when their R_s values were low coincided with periods when the soil moisture content was high, and while the moisture content measured at 5 cm depth was never high enough to hinder decomposition, the conditions deeper in the soil profile may have repressed decomposition and/or the gas flux. Other authors have reported similar fluctuations in R_s, with occasionally low values (Pumpanen et al., 2004, Mallik and Hu, 1997), albeit attributing them to low soil moisture contents. In the second year, fluxes from DHL areas had stabilized and were similar to those recorded in INT areas.

At the Stadra and Fågelfors sites no significant difference in R_s between the MIX and INT areas was detected (Fig. 7). At Åmot, R_s was initially higher in MIX areas than in INT areas, but this difference had disappeared after a month (Fig. 7). In the second year following disturbance, the R_s values associated with MIX areas were lower than those associated with INT areas at Åmot.
Hypothesis II, that mixing mineral soil and organic matter would increase the R_s, was therefore rejected, as the R_s values recorded in MIX areas were not higher than those recorded in INT areas at any of the study sites, except in the first month in the Åmot experiment (possibly because any increase in R_s that MIX-creating disturbance induces is very transient).

A potentially significant factor is that mixing the soil disrupts the mycelium of soil fungi. The destroyed mycelium, in addition to other easily decomposable material made available by mixing, becomes a substrate for opportunistic saprotrophs, which can respond to changes quickly (Lindahl et al., 2010).

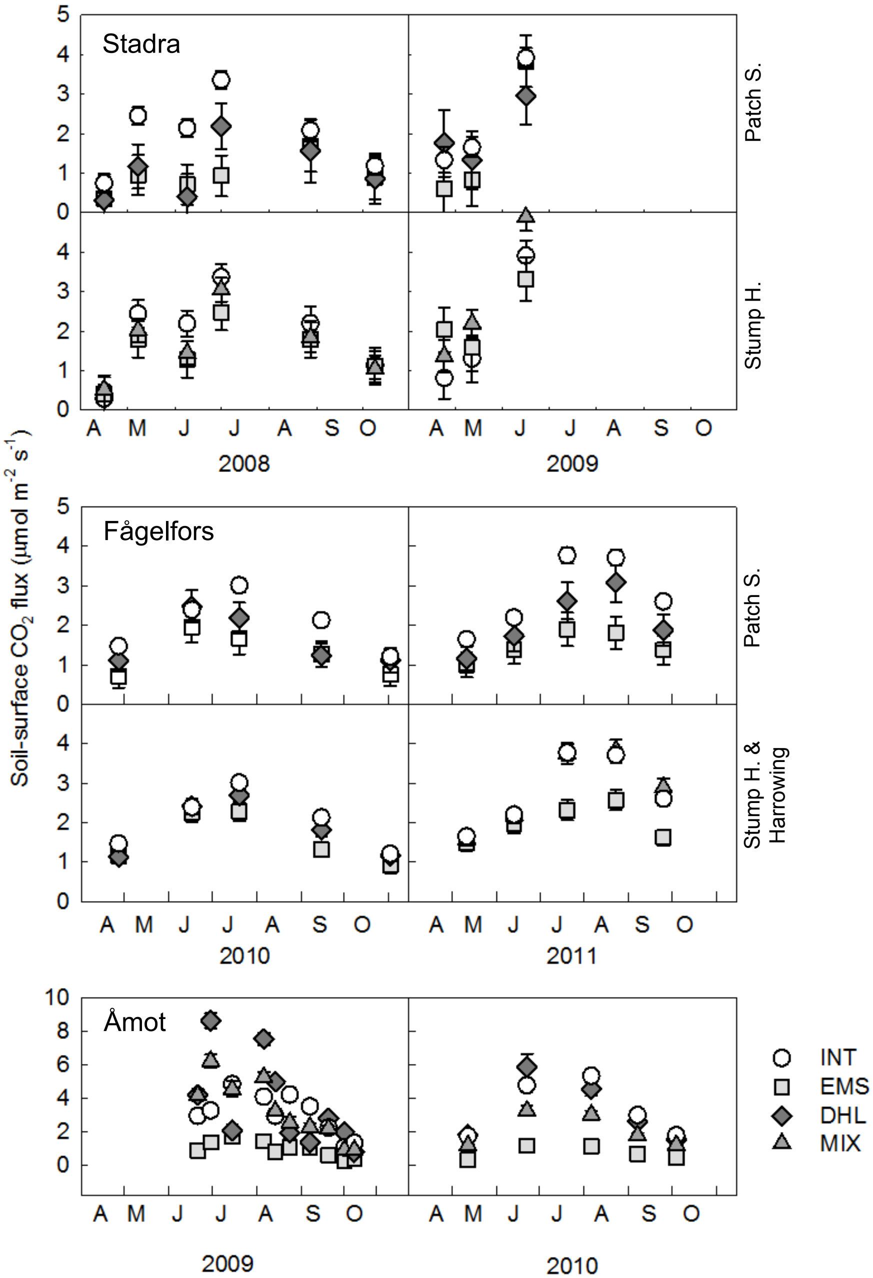

Figure 7. Soil-surface CO_2 fluxes measured in areas Soil-surface CO_2 fluxes recorded in areas assigned to indicated soil disturbance classes in clear-felled areas (INT- intact soil, EMS- exposed mineral soil, DHL- double humus layer, MIX- Mixed humus layer with mineral soil) at: Stadra in the patch scarified plots (top) and stump harvested plots (bottom) in 2008 and 2009; at Fågelfors in the patch scarified plots (top) and both harrowed and stump harvested plots (bottom) in 2010 and 2011; and at Åmot 2009 and 2010. Bars denote standard errors, and the X axis shows months (capital letters denoting the months from April to October).

5.2.3 Differences in R_s responses between the site preparation methods and stump harvest

To obtain overall estimates of R_s per unit area following the considered site preparation methods and stump harvest, the values obtained for areas assigned to each soil disturbance class were scaled in proportion to their areal cover at each site. At Karlsheda, R_s responded positively to stump harvest initially (Fig. 8); on average, CO_2 emissions were 60% higher from stump-harvested plots than from the undisturbed control plots during the first two weeks. This increase was a result of higher emissions from areas assigned not only to the MIX and DHL disturbance classes, but also the INT class (which appeared to be undisturbed by eye). However, this increase was highly transient; after two weeks there was no difference in this respect between stump-harvested plots and the undisturbed controls.

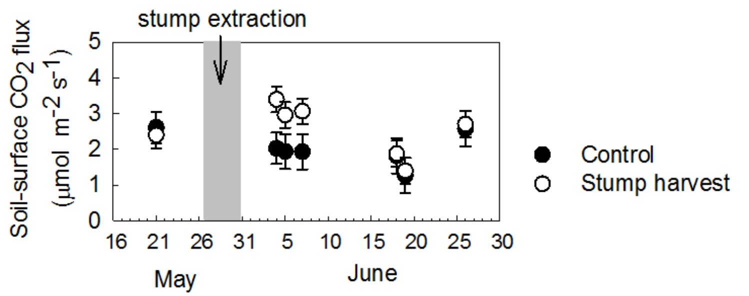

Figure 8. Mean soil-surface CO_2 fluxes in stump-harvested plots (open circles) and control plots (filled circles) at Karlsheda in South Sweden, 2008. Bars denote standard errors.

At the Stadra and Fågelfors sites, where responses were monitored over two years, no significant differences in R_s were found following the stump harvest, patch scarification and harrowing treatments (Fig. 9). The annual mean R_s values estimated for site-prepared and stump harvested plots were lower than estimates for the INT areas (Table 2). In the first year, R_s estimates associated with areas representing all visible disturbance classes resulting from all site preparation and stump harvesting treatments were around 10% lower than those associated with INT areas (Table 2). Similar R_s values were obtained in the second year, except for patch scarified areas in Stadra, where the annual mean R_s was 3% lower than that obtained for INT areas.

The mean R_s values for each disturbance class at the Åmot site were scaled up to cover the entire measuring period (June to October) each year, then multiplied by their respective proportions of disturbed area to obtain estimates of overall fluxes per unit area associated with each treatment (Fig. 5). The results indicate that the site preparation and stump harvest practices induced stronger R_s responses than at the Stadra and Fågelfors sites. More specifically, during the first year, patch scarification, harrowing and stump harvesting decreased R_s by 7%, 11% and 25%, respectively, relative to fluxes from intact soil. In the second year, the calculated fluxes from the patch scarified, harrowed and stump harvested areas were 11%, 44% and 55% lower than fluxes from the INT areas, respectively (Table 2). The annual R_s values derived for these areas may have been higher at Åmot than at the other sites because the large, coherent areas (2×2 m plots) enhanced effects of the disturbances, as the R_s values reflect solely fluxes associated with the corresponding disturbance classes. In contrast, transitions or border effects may have confounded results at Stadra and Fågelfors.

Hypothesis III, that increases in the area affected by disturbance will result in higher reductions in soil C stocks, due to increased R_s, was therefore rejected. The findings indicate rather reductions in R_s following patch scarification, harrowing and stump harvesting in comparison to INT areas at all study sites

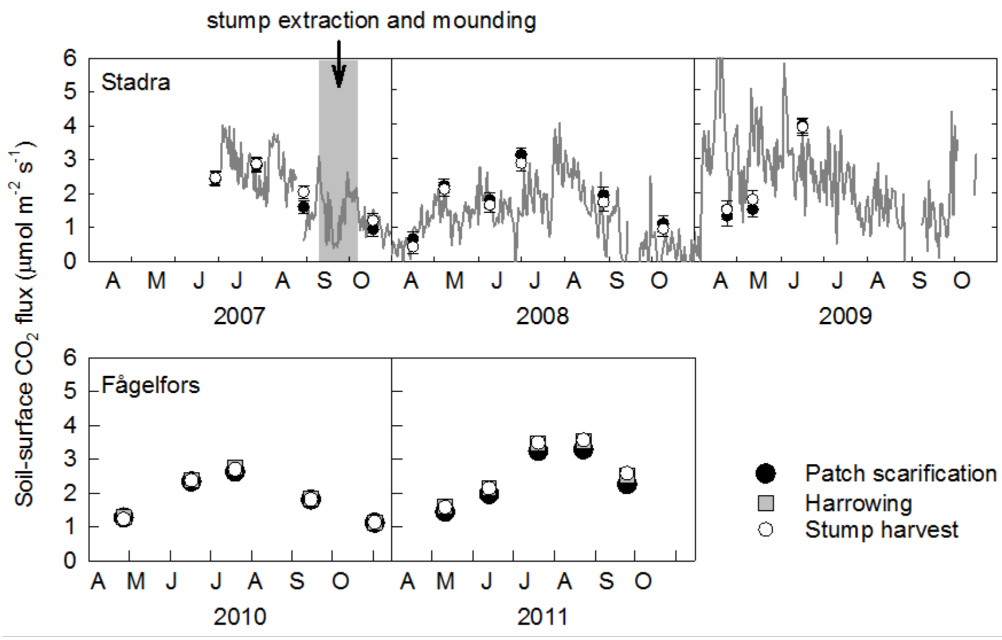

Figure 9. Soil-surface CO_2 fluxes after patch scarification, harrowing, and stump harvest at Stadra and Fågelfors. The X axis shows time, with capital letters denoting the months from April to October. Bars denote standard errors. The gray line in the Stadra panels shows the soil-surface CO_2 flux obtained from the eddy-flux measurements.

Table 2. *Mean annual soil-surface CO_2 fluxes after patch scarification (Patch S.), harrowing (Harrow), and stump harvest (Stump) relative to the mean value for areas assigned to the soil disturbance class intact (INT, 100%) at Stadra, Fågelfors and Åmot in years 1 and 2 after treatment. The values for Åmot have been scaled up assuming that proportional areas covered by the soil disturbance classes following the treatments were as shown in Fig 5.*

	Year 1				Year 2			
Site	Intact	Patch. S	Harrow	Stump	Intact	Patch S.	Harrow	Stump
Stadra	100%	90%		84%	100%	97%		100%
Fågelfors	100%	90%	92%	90%	100%	88%	96%	98%
Åmot	100%	93%	89%	75%	100%	89%	56%	45%

5.2.4 Uncertainties in R_s

An assumption underlying all of the studies was that R_s in the treated areas was dominated by heterotrophic respiration, with negligible contributions from autotrophic respiration. This appears to be valid for stumps left at the sites, as girdling experiments in boreal forests have shown that autotrophic respiration ceases within two weeks to two months after tree girdling (Olsson et al., 2005, Högberg et al., 2001). Furthermore, the field vegetation during the study periods was very sparse, and the measurements acquired using the eddy-covariance system in Stadra did not reveal any clear signs of CO_2 uptake by plants during daytime (Fig 9). During the second year, no vegetation was visible in April and May; however, it started to recover in June, and in August, the area was mainly covered by *Deschampsia flexuosa* at all the sites. The higher R_s values in the second year, recorded at all sites, may therefore have been caused by ground vegetation. The ground vegetation was harvested at the Stadra site in August 2009, and there was no difference in its amount between the patch scarified and stump harvested plots. At Fågelfors, the biomass of the ground vegetation was assessed in August 2011 and found to be the same in all the plots (and lower than typically present in clear-cuts with full established ground vegetation). These findings suggest that autotrophic respiration was of similar magnitude in all the plots, and of little importance for overall emissions.

Another assumption was that CO_2 evolution from decomposition of fresh roots and stumps was negligible during the measuring periods. If this premise was incorrect, the minor amount of fresh roots and stumps on stump-harvested plots could counteract the assumed impact of soil disturbance. At Stadra, stumps and root systems corresponding to 1.9 kg C m^{-2} were harvested in the stump-harvested treatments (Paper I). Assuming that roots and stumps decompose as described by Hyvönen and Ågren (2001), about 6 g C m^{-2} and 16 g C m^{-2} would have been released from this pool in the first and second years, respectively. These rates correspond to fluxes of about 0.05 and 0.13 µmol

CO_2 m^{-2} s^{-1} during the summers of the first and second years, respectively. These figures are based on the assumption that decomposition of this pool follows the same annual pattern as the R_s measured by the eddy-covariance system. Compared to the soil R_s from all the sites, this would be a small fraction and would not affect the conclusions presented in this thesis.

It should also be noted that little attention was paid to wheel-ruts as a disturbance class in the studies. However, they warrant further investigation as severe rutting can reduce CO_2 emissions, but if they are filled with water (as observed at Stadra), they may result in more extensive methane (CH_4) emissions, thereby countering any reduction in CO_2 emissions in terms of overall greenhouse effects (Schlesinger and Bernhardt, 2013)

5.3 Litter decomposition (Paper III)

Results from the incubations of needle and root litter at the Åmot site indicate that placement of the litter affects its decomposition rates more strongly than the disturbance class. As shown in Fig 10, litter consistently decomposed more slowly in litterbags placed on the soil surface than in bags buried in the soil (see Fig. 3 for the placement of bags in plots subjected to each treatment). Litter decomposition is generally assumed to be controlled by litter quality, activities of organisms, and site-specific environmental conditions, including temperature and moisture. Notably, according to a significant body of studies, the first-year mass losses of Scots pine needle litter are related to climatic factors (Johansson et al., 1995 Johansson, 1994, Berg et al., 1993, Fox and Cleve, 1983). Accordingly, variations in soil moisture and temperature at the Åmot site, associated with variations in both the disturbance classes and locations of the litterbags (soil-surface versus buried), could explain the observed differences in decomposition rates. Several studies have also shown that litter decomposes more slowly in clear-cuts than in closed forest (Palviainen et al., 2004, Prescott et al., 2000), possibly because the soil surface layers are drier, due to the greater direct exposure to wind and sunlight when the forest floor is no longer protected by the canopy cover (Prescott et al., 2000). This may also explain the slower decomposition rates in litterbags placed on the soil-surface, relative to rates recorded when the litter was buried in the soil or placed between humus layers. Thus, the lower decomposition recorded for litter placed on top of the soil further supports the hypothesis that low moisture is a primary factor limiting the decomposition of exposed litter in clear-cuts. These findings also suggest that site preparation methods that move organic material deeper into the soil profile may induce higher losses of litter C, at least during the first subsequent years.

Furthermore, the results from the Åmot study showed that root decomposition was insensitive to soil mixing, in accordance with the R_s results pertaining to MIX areas during the first year, but conflicting with the leveling of R_s in MIX areas observed in the second year. The difference between the results yielded by the two methods may be linked to the increasing recalcitrance of litter during decomposition (Berg, 2000), as the *in situ* measurements of R_s included emissions from the total soil organic C stock and cohorts, while the litterbag study followed the decomposition of newly shed needle litter. The average age of a humus layer in Scandinavia is 40 years, according to a study with ^{14}C tracers by Fröberg et al. (2011), indicating that the new litter is only a small fraction of the total humus layer.

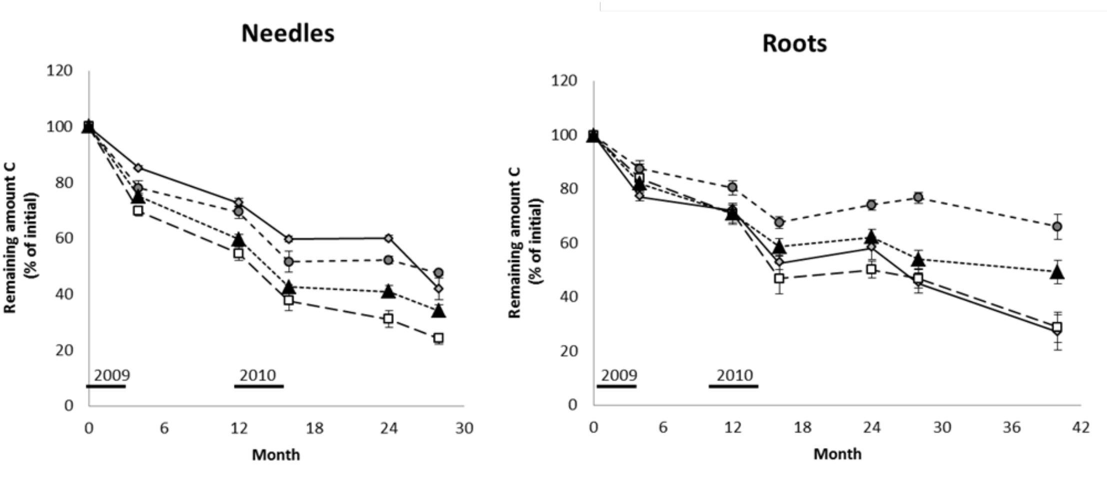

Figure 10. Decomposition, expressed as the proportion (%) of C remaining in the litterbags containing needle and root litter, in areas assigned to intact soil (INT), exposed mineral soil (EMS), double humus layer (DHL), and mixed soil (MIX) disturbance classes. The initial C concentration in the needles and roots was 55%. It should be noted that incubation started in June 2009 (month 0), so months 7, 19 and 31 refer to January. Black lines just above the x axis indicate the time-periods when soil-surface CO_2 flux (R_s) measurements were conducted.

5.4 Long-term effects of site preparation (Paper IV)

The long-term effects on C stocks of site preparation were studied in the experiments with *P. sylvestris* and *P. abies* at Fläda, and *P. contorta* at Rätan. In all three cases, the total ecosystem C stocks were lower in control plots than in plots subjected to the site preparation treatments (Table 3, Fig. 11). There were no significant overall differences in ecosystem C stocks between plots subjected to different site preparation methods, but they tended to be highest following ploughing, lowest following harrowing and intermediate following mounding. The between-treatment differences in ecosystem C stocks were mainly due to differences in tree C stocks. In the experiment with pine at Fläda, the ecosystem C stocks were significantly lower in the control and harrowed plots than in the mounded and ploughed plots. The differences in ecosystem C stocks between the site preparation methods and controls reflected those noted in tree C stocks (Table 3, Fig. 11). These results are consistent with previous indications that site preparation has a positive long-term effect on tree growth (e.g., Mattson, 2002, Örlander et al., 1996).

The most intense site preparation methods, ploughing and mounding, resulted in higher tree C stocks than the control and harrowing treatments (Table 3, Fig. 11). These findings indicate that site preparation has a positive effect on tree growth and production, as well as survival rates during the first years (e.g., Mattson, 2002, Örlander et al., 1996).

P. abies stands are more productive than *P. sylvestris* stands on fertile, mesic sites, as at Fläda (Ekö et al. (2008). Conflicting with these findings, the tree biomass was lower in the *P. abies* plots than in corresponding *P. sylvestris* plots at the Fläda site, 24 years after treatment (Fig. 11). However, it should be noted that the *P. abies* stands were severely affected by frost, pine weevil attacks, grass competition and *Melampsora* rust disease, leading to up to 90% mortality in control plots during the first years (Sugg, 1990). In addition, despite additional supplementary plantation, *P. abies* never established properly, and the site was further invaded by *P. sylvestris* and *B. pendula*. The site conditions proved more favorable to *P. sylvestris*, for which mortality rates were much lower (around 10%) during the first three years (Sugg, 1990).

Table 3. *Significant effects (*, $p < 0.0$; **, $p < 0.01$; ***, $p < 0.001$) of experiment, treatment (SPM site preparation method) and experiment x treatment interaction on C and N stocks in whole ecosystems, tree biomass, ground vegetation, humus layer and mineral soil according to the overall ANOVA for all experiments (top three rows) and experiment-specific ANOVAs (bottom three rows).*

Fixed effect/ site	Ecosystem	Tree	Ground layer	Humus layer	Mineral soil (0-25 cm)	Soil
Site	*	*	*	*	***	**
SPM	*	*	0.07	0.51	*	0.55
Site*SPM	0.89	0.94	*	0.47	0.07	0.31
Each site/SPM						
Fläda (P)	0.08	0.09	0.66	0.16	0.41	0.30
Fläda (S)	0.12	*	*	0.71	0.06	0.19
Rätan	0.26	0.31	0.17	0.63	0.16	0.79

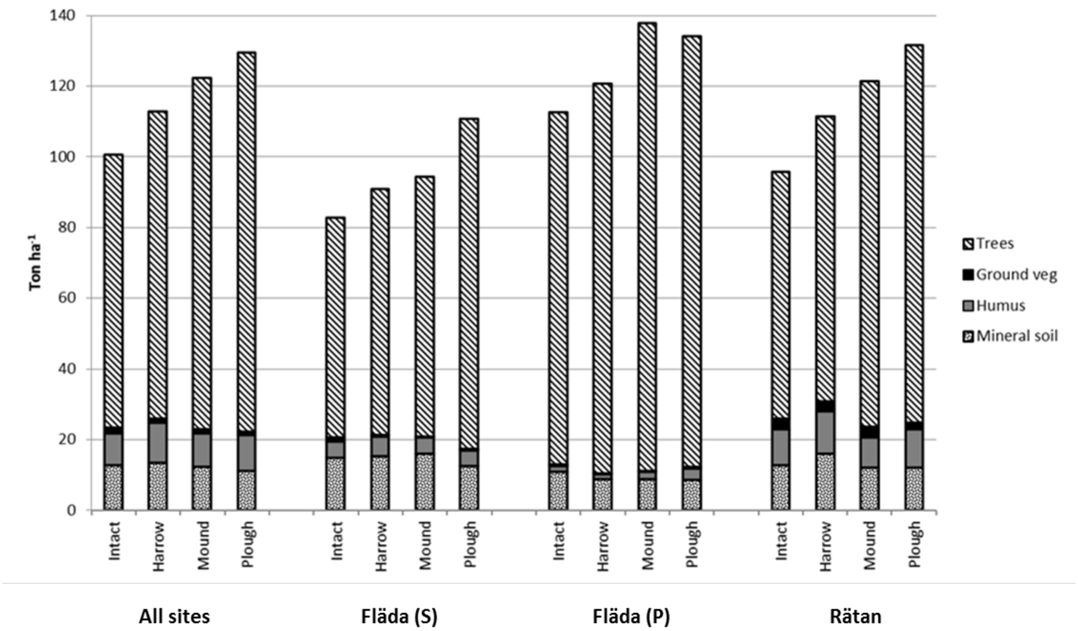

Figure 11. Average carbon stock (ton ha^{-1}) in the entire ecosystem, tree biomass, vegetation layer, humus layer and top 25 cm of mineral soil in intact areas (intact) and plots subjected to the following site preparation treatments: harrowing (harrow), mounding (mound) and ploughing (plough). Fläda (S) and (P) refer to the *Picea abies* and *Pinus sylvestris* experiments at Fläda, respectively.

The ground vegetation contributed small fractions of the overall ecosystem C stock (0.5% to 5%) (Fig. 11). There were no general treatment effects on C stock in ground vegetation, but in the Fläda experiment with *P. abies*, the ground vegetation C stock was higher in the control plots than in the site-prepared plots (Table 3).

There was no difference in the C amount in the humus layer between treatments (Table 3). However, the C contents in the mineral soil were lower after ploughing (11 ton ha^{-1}) than in the control and harrowed areas (13 ton ha^{-1} in both cases: Fig. 11, Table 3). In the *P. abies* experiment at Fläda, the mineral soil C stock was lower (12 ton ha^{-1}) 24 years after site preparation by all tested methods than in control plots (around 15 ton ha^{-1}). However, this outcome was not observed in the other experiments. Similarly, Nordborg et al. (2006) found no changes in the total amount of soil C 10 years after site preparation at sites with a wide range of Swedish soils. Egnell et al. (2015) also found that two site preparation methods representing extremes of intensity (deep ploughing combined with stump harvest, and mild manual patch scarification) resulted in no significant differences in soil C stocks two decades later.

These results confirmed hypothesis IV, that due to enhanced tree growth the C stock in vegetation (trees, root and field vegetation) generally increases with increases in the intensity of site preparation (Fig. 11).

5.4.1 Uncertainties

Generally, forest soil C stocks have large spatial heterogeneity, even within a small area (Muukkonen et al., 2009, Webster, 2000, Wilding et al., 2000). Soil C stocks also vary vertically, as concentrations generally decrease with depth (e.g., Liski and Westman, 1997). This heterogeneity causes large standard errors in measurements of soil C stocks, complicating efforts to detect changes in soil C stock resulting from site preparation. Furthermore, site preparation creates mounds and tilts with higher soil surfaces, and furrows with lower surfaces, than undisturbed areas. This complicates sampling because, for instance, if the soil surface in the undisturbed areas is used as a reference level, samples in the furrows will be taken from a lower depth relative to those in undisturbed areas (see Fig. 4 in *Materials and Methods*). Moreover, samples from a mound or tilt will not extend to the same relative depth as samples from the undisturbed areas, and in the former case, a double humus layer is imbedded in the soil. This raises questions regarding whether any detected changes in soil C stocks are effects of tested site preparation methods or artifacts associated with the sampling method.

To test possible effects of such artifacts, sampling outcomes directly after site preparation were estimated using data provided by Callesen et al. (2003). The results, assumed to pertain to the vertical distribution of mineral soil C stocks in a typical northern boreal, medium texture soil (Table 4), indicate that samples taken following the mounding and harrowing site preparation methods would have 110% and 120% higher mineral soil C stocks than samples from undisturbed control plots, while samples from ploughed plots would have 60% lower mineral C stocks (Table 4).

The ploughing site preparation treatment applied at Fläda and Rätan was intensive, with depths of around 50 cm in the furrows, compared to the undisturbed areas between them. A few mineral soil sample samples (three out of 19) included an embedded double humus layer, however no such layers were detected in any designated "tilt" samples. This finding indicates that ploughing formed a double humus layer that was buried deeper than 30 cm in the soil horizon and not sampled in the Fläda and Rätan studies. Similarly, Nordborg et al. (2006) found that ploughing-based site preparation markedly changed the distribution of C in the soil profile, shifting the humus layer to substantially greater depths and (thus) resulting in higher C contents in the 30 to 50 cm layers.

However, the differences in estimated soil C stocks resulting from adjustments of the calculations are small compared to the increase in stocks associated with the increases in tree biomass, indicating that at the ecosystem scale by far the most important consequence of site preparation is enhancement of the reestablishment and growth of the trees.

Table 4. *Calculated effects of sampling method on estimated mineral soil C stocks following indicated treatments directly after site preparation. Treatment depths of 30 cm are assumed for mounding and harrowing, and 50 cm for ploughing. Soil samples were assumed to be taken down to 30 cm depth.*

	Treatment	Area affected (%)			Mineral soil C stock	
Treatment	depth (cm)	Intact	Mound	Furrow	Ton ha^{-1}	% of intact
Intact	0	100	0	0	12	100
Mound	30	75	12.5	12.5	13	110
Harrow	30	50	25	25	15	120
Plough	50	30	35	35	7	60

6 Conclusions

The conclusions presented in this thesis indicate that site preparation and stump harvest do not lead to reductions of soil C stocks and that, in the long-term, the forest growth is the most important determinant of whole ecosystem C stocks. Specific conclusions from the studies the thesis is based upon include the following:

- The overall effect of site preparation and stump harvest on soil-surface CO_2 flux is none or a reduction, compared to intact areas.
- Any initial increase in soil-surface CO_2 fluxes after site preparation and stump harvest is transient and limited to the first few weeks.
- Removal of the humus layer, exposing the mineral soil, leads to lower soil-surface CO_2 fluxes, and creating a double humus layer does not lead to higher soil-surface CO_2 fluxes, compared to control fluxes.
- Mixing the humus layer and mineral soil does not lead to higher soil-surface CO_2 fluxes, and may even lead to their reduction.
- The location of incubated litter strongly influences the decomposition rate, as rates were higher in buried litterbags than in bags placed on top of the soil. Mixing the soil will move litter cohorts to new locations in the soil horizon, raising some to the surface and burying others deeper in the profile.
- Burying needle litter and fresh roots in horizons more favorable for decomposition did not lead to higher soil-surface CO_2 fluxes from the entire soil profile.
- Site preparation increases whole forest ecosystem C stocks by enhancing tree establishment and growth rates.

7 Future research

The forest C pool is large and many factors affect how it responds to manipulative disturbances and environmental change. The studies underlying this thesis focused solely on responses at sites with Swedish podzolic, mesic to dry soils. In order to understand effects of specific kinds of disturbances on C cycling and pools, as well as the processes involved, investigations focusing on other types of sites with different soil and climatic conditions are required. Methodological improvements are also needed (e.g. sampling down to a reference level below furrow depths) and/or application of complementary methods, such as isotope labelling, sampling soil solutions and modelling to estimate full soil C budgets.

The studies also ignored effects of wheel-ruts, which could significantly influence the results of the considered practices if they result in severe rutting affecting substantial areas. Machines are needed to harvest the standing forest, transport the stems and residuals, and prepare sites. When stumps are harvested, the force exerted by dragging up the roots can damage soil under the machines. Stump harvesting also requires more turns in and out of clear-cuts, when the stumps are first piled up to dry and subsequently transported. Nevertheless, too little attention has been paid to the consequences of wheel-ruts in Nordic countries, and they require more research.

Effects of site preparation and stump harvest on fluxes of other greenhouse gases, especially CH_4 and N_2O, also require thorough investigation in order to acquire a comprehensive understanding of their potential contributions to mitigating climate change. When the water table rises after a final harvest (due to the sharp reduction in evapotranspiration), accompanied by disturbances that may extend below the water level, the balance between its production and consumption will be shifted towards production. As CH_4 and N_2O have such large global warming potential even small changes in their emissions due to soil disturbance may have profound climatic implications, which require careful analysis.

8 Sammanfattning (Swedish summery)

Att minska utsläppen av växthusgaser är en stor utmaning i dagens samhälle. Träden i skogar och annan växtlighet binder upp stora mängder kolidoxid från atmosfären och bygger upp kolförråd i form av biomassa och organiskt material i marken. Skogsekosystemet är därför en viktig beståndsdel i den globala kolcykeln och därmed också viktig vid klimatdiskussioner. Denna avhandling behandlar hur det boreala skogsekosystemets kolförråd påverkas av markberedning och stubbskörd. Kolförrådet i svensk skogsmark, som består av organiskt material i mineraljord och humus, är dubbelt så stort som det kolförråd som finns i biomassan. Det motsvarar 100 gånger så mycket kol som de årliga utsläppen av fossila bränslen i Sverige. Vid både markberedning och stubbskörd uppstår olika typer av störningar: ytor som består av bar mineral jord, ytor med ett dubbelt humuslager och/eller kraftigt omrörda ytor där humus blandas med mineraljord. En farhåga har varit att dessa störningar påskyndar nedbrytningen av markkolet och därmed minskar kolförrådet vilket vore negativt ur klimatsynpunkt. Å andra sidan skulle markstörningarna kunna förbättra etableringen och tillväxten av det nya beståndet, vilket skulle gynna kolinbindningen på lång sikt. Stubbskörd kan även bidra till klimatnyttan genom att ge ett tillskott till bioenergi och kan därmed ersätta fossil energi.

För att kunna beskriva hur markens och skogsekosystemets kolbalans påverkas av markberedning och stubbskörd på kort- och lång sikt har sex fältförsök i södra och mellersta Sverige använts. På fyra försök, där initiala effekter (upp till fyra år) studerades, gjordes analyser av markrespiration, d.v.s. koldioxidflöden från markytan, och mätningar av marktemperatur och markfuktighet. På en av dessa försökslokaler mättes även nedbrytningshastighet av barr och grova rötter med hjälp av förnapåsar. På ytterligare två försökslokaler undersöktes långsiktiga effekter på kolbalansen genom att mäta kolförråd i mark och biomassa.

Skattningar av hur stor andel av markytan som störs vid markberedning respektive stubbskörd och vilken typ av störning (bar mineraljord, dubbelt humuslager eller omrörd humus och mineraljord) som metoderna ledde till bestämdes på tre av fältförsöken. Stubbskörd var den metod som påverkade störst andel av markytan (70 %), där 50 % bestod av omrörda markytor och 20 % av bar mineraljord. Harvning påverkade 60 % av markytan, där 25 % bestod av mineraljord och 45 % av tiltor. Fläckmarkberedning var den metod som påverkade minst del av markytan (30 %) och störningen utgjordes där av lika delar bar mineraljord och dubbelt humuslager.

Koldioxidflödena, från de olika typerna av störningar av markytan, mättes på fyra av fältförsöken under två år. I de områden där humuslagret togs bort och bar mineraljord exponerades minskade markrespirationen i förhållande till ostörda kontrollområdena. Från områden som består av ett dubbelt humuslager kan man förvänta sig högre markrespiration på grund av en ökad mängd organiskt material, men värdena i våra studier var av samma storlek som kontrollområdena. Detta kan bero på att fuktigheten även förändras, så att nedbrytningen hämmas. I de områden där humuslagret och mineraljorden rördes om kraftigt, kunde en ökning observeras under de första två veckorna, men efter det var markrespirationen på samma nivå som kontrollytorna. I ett fältförsök ledde omrörningen till och med till lägre respiration än ostörda ytor. Det visar att omrörning av marken inte leder till ökad markrespiration, vilket är motsatt mot vad många tidigare studier har kommit fram till. Sammanfattningsvis visar markrespirationsmätningarna att den totala effekten av markberedning och stubbskörd minskar eller inte påverkar markrespirationen jämfört med ostörda ytor. Det var vidare inga signifikanta skillnader mellan markberedning och stubbskörd.

I ett av fältförsöken studerades nedbrytningen av barr under tre år och nedbrytningen av grovrötter under fyra år. Här placerades förnapåsarna där majoriteten av barren eller rötterna skulle ha legat efter en markberedning eller stubbrytning, d.v.s. uppe på markytan, mellan de dubbla humuslagren eller nedgrävda i mineraljorden. Resultaten visade att placeringen av förnapåsarna var det som främst påverkade nedbrytningshastigheten; förnapåsar med nergrävda barr och rötter hade en högre nedbrytningshastighet än de som var placerade på ytan.

Hur markberedning och stubbskörd påverkar kolet i ekosystemet på lång sikt studerades i två fältförsök med hjälp av markprovtagning och skattning av biomassan ovanför marken. Försöken inkluderade högläggning, harvning, plogning och en kontroll (och ytorna planterades med tall, gran samt contortatall). Efter ca 25 år hade alla markberedda ytor högre mängd kol i ekosystemet än kontrollen. Detta berodde på en ökad trädtillväxt, medan markens kolförråd inte hade påverkats.

Den viktigaste slutsatsen i denna avhandling är att markberedning och stubbskörd inte leder till någon minskning av markkolet, varken på kort eller lång sikt. Det bästa sättet att öka inbindningen av kol i skogsekosystemen är således att välja den markberedningsmetod som ger bäst tillväxt.

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Acknowledgements

Research funding was obtained from the Department of Soil and Environment at the Swedish University of Agricultural Sciences (SLU), the Faculty of Natural Resources and Agricultural Sciences (SLU) together with the Swedish Energy Agency as part of the program ''Tree Stump Harvesting and its Environmental Consequences''. I take the opportunity to thank all coordinators and co-workers in the different programs. It has been a pleasure to work with you!

Many people have been involved in the process of finishing this thesis. In particular, I want to thank:

- My first main supervisor, Maj-Britt Johansson, for introducing me to the world of science. I have truly enjoyed your enthusiasm and great knowledge. I'll always remember our adventures in Russia, Wales and Italy.
- My second main supervisor, Ewa Bringmark, for always having a positive attitude and taking time for discussions.
- My third main supervisor, Annemieke Gärdenäs, for pulling the last strings together while finishing my thesis and manuscripts, both in the writing and all administrative work around it. You have always read my papers with a great enthusiasm and returned it with thoughtful and wise comments. You have been "pricken över i:et".
- A special thanks to the only supervisor how has been with me during the entire PhD-project, Monika Strömgren: for always taking the time discussing field work, data analyses, reading both manuscripts and thesis, and unbending all my question marks. I could not have done this without you!
- My co-supervisor, Lage Bringmark, for all support and fruitful discussions.

- My co-supervisor, Hans-Örjan Nohrstedt, for all the time you devoted reading my manuscripts and thesis and for all your valuable comments and constructive inputs.
- Claudia von Brömssen and Mikael Andersson Franko for valuable statistical input.
- Anna Mårtensson, Johan Arvidsson and Jon-Petter Gustavsson for valuable comments on my thesis.
- All of you that helped me with my field-work throughout the years: Kenth Andersson, Cecilia Sandström, Frida Hartman, Erik Rosengren, Cecilia Brolin, Lena Henrysson, Elisabet Nilsson, Linnea Hedlöf, Harriet Henrysson, Amanda Aldebert and Annie Henrysson
- Everyone around the coffee-table. What would the day look like without all nice talk at the fika?
- Gertrud Nordlander for being my lunch partner over the years.
- Linnea Hansson with whom I joyfully shared my office. Thanks for all the nice talk about everything and nothing over the past years.
- All the people I've forgotten to mention here.
- And last my family, Lars, Helmer and Elvin for being who you are.