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Soil CO_2 Flux During the First Years After Stump Harvesting in Two Swedish Forests

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One way of increasing the supply of renewable energy, thereby decreasing the use of fossil fuels, is to extract the stumps that remain after final stem harvesting. However, little is known about the environmental consequences of stump harvesting, and how ecosystem services, such as carbon sequestration, are affected by the practice. In the present paper, the effects on the soil carbon pool during the first months and years after stump harvesting in former Norway spruce stands are presented. The study was performed at two sites in mid- and southern Sweden. At both sites, the soil CO_2 flux was measured on several occasions with a portable respiration system, to compare plots on which stump harvesting had occurred, with reference plots. At one of the sites, CO_2 exchange was also followed continuously by means of eddy-covariance measurements before and after stump harvesting. Since there was no vegetation at the beginning of the study, almost all emitted CO_2 could be assumed to come from heterotrophic sources, and the soil CO_2 flux was measured. This study shows that the effect of stump harvesting on CO_2 flux or soil decomposition processes is small or absent compared to site preparation such as mounding in a short-term perspective of months and years. The long-term consequences of stump harvesting are, however, still uncertain.

Keywords C stock, *Picea abies*, site preparation, soil C, soil disturbance, soil respiration, stump removal
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1 Introduction

Worldwide, renewable energy is promoted by national and international policies as a contribution to the mitigation of climate change. The European Union (EU) has set the target of a 20% share of renewable energy sources in energy consumption by 2020; according to national targets, Sweden is to increase its share of renewable energy sources from 39% to 49% (EU 2009). Approximately half of the renewable energy supply in Sweden is currently derived from forest bioenergy, and less than 1% from agricultural sources (EU 2009). However, there is a large potential for increasing the share of both forestry and agriculture. One way of increasing the supply of renewable energy sources, thereby decreasing the use of fossil fuels, is to extract the stumps that remain after final stem harvesting. The biomass in the stumps and coarse roots corresponds to almost half of the biomass stored in stems in a mature forest (Egnell et al. 2007, cf. Marklund 1988). However, little is known about the environmental consequences of stump harvesting, and how ecosystem services are affected by the practice (Egnell et al. 2007). Stump extraction causes soil disturbance, which in turn can lead to an increase in decomposition of soil organic matter and a decrease in soil carbon pools (e.g. Johansson 1994, Lundmark-Thelin and Johansson 1997, McLaughlin et al. 2000). To be able to assess the extent to which stumps can be considered as a carbon-neutral energy source, it is necessary to evaluate the indirect effects of stump extraction on soil carbon that are associated with CO_2 emissions from the soil.

Much more carbon is stored in soil than in biomass in temperate and boreal forests (Houghton et al. 2001). A change in the factors that affect the decomposition and sequestration of carbon will also affect the carbon pools, and may transform a carbon pool from a sink to a source or *vice-versa*. Many studies have been carried out on the response of soil carbon to different forest-management practices (Johnson and Curtis, 2001, Freeman et al. 2005, Hyvönen et al. 2007), but studies on how stump harvesting affects soil carbon pools are very rare (Walmsley and Godbold 2010). One study of five forest soils in northwestern USA, 22–29 years after stump harvesting, indicated that a reduction in soil organic matter had occurred (Zabowski et al. 2008). Hope (2007) found indications of a decrease in mass of the Mor layer nine years after stump harvesting. He also found that the carbon content of the mineral soil had increased. Another way of studying changes in the soil carbon pool is to measure the soil CO_2 efflux. We are not aware of any published data from stump-harvested sites, but Pumpanen et al. (2004) examined the soil CO_2 flux following different disturbances or treatments of forest soil. They found higher fluxes where the organic matter was mixed with the mineral soil, as compared to intact soil. It has also been shown that most of the fresh, easily decomposable organic matter appears to decay during the first summer after clear-felling (Pumpanen et al. 2004, Berg et al. 1984, Prescott et al. 2000).

The results of studies on site preparation can indicate how soil organic matter is affected by soil disturbance. Johnson (1992) concluded in his review that site preparation leads in general to soil carbon loss. However, none of the studies included in the review was representative of northern upland soils. There are still only a few studies of the effects on soil carbon (Freeman et al. 2005, Hyvönen et al. 2007), and their results are contradictory. One reason for this may be that some only studied the humus layer and reported a decrease, whereas conclusions for the entire soil profile are missing. A Swedish study that covered a range of forest soils found no change in the total amount of carbon, but found a changed distribution of carbon in the soil profile (Nordborg et al. 2006). Another reason could be differences in the intensity of site preparation. It is reported that carbon loss after site preparation increases with the intensity of soil disturbance (Johansson 1994, Schmidt et al. 1996, Örlander et al. 1996, Mallik and Hu 1997). There are, however, suggestions that the soil disturbance associated with stump harvesting can be greater than that from traditional site preparation (Hyvönen-Olsson and Grelle 2007). Loss of soil carbon could therefore be greater after stump harvesting than after traditional site preparation.

The aim of this study is to investigate, for two Norway spruce sites in Sweden, how stump harvesting affects the soil-surface CO_2 flux during the first years after the stump harvest. Our hypothesis is that mixing of the soil profile, caused by stump harvesting, will increase the decomposition of soil organic matter, and will therefore increase the soil-surface CO_2 flux. The hypothesis is based on the assumption that the soil-surface CO_2 during the first year(s) after clear-felling is dominated by heterotrophic respiration, since autotrophic respiration is small or absent after clear-felling of a mature, closed forest, when there are no living tree roots and when ground vegetation is sparse. Another assumption is that the respiration derived from decomposition of the pool of fresh roots and stumps is small or negligible during the first period after final harvesting. Stump-harvesting decreases the amount of coarse woody debris in the soil, which would lead to a decrease in respiration. However, the delay before fresh, coarse woody debris is colonised by decomposers is quite long (Harmon et al. 1986; see also Hyvönen and Ågren 2001), and CO_2 release from stumps and coarse roots might therefore be assumed to be negligible shortly after harvest. If these two assumptions are correct, the measured flux of soil-surface CO_2 is directly linked to the carbon stock in the soil, and the measured flux corresponds to a loss of the same magnitude in the soil-carbon pool.

2 Materials and Methods

2.1 Site Description

The studies were made on two sites: Karlsheda in south Sweden and Stadra in mid-Sweden. The Karlsheda experiment was a short-term study (one month), whereas that at Stadra lasted for 2.5 years. The former forest stands were Norway spruce (*Picea abies* (L.) Karst.) of rather high productivity, and the soil at both sites is a podozolic, glacial till (Table 1). Soil characteristics, climate and forest management for the two sites are further described in Table 1.

Table 1. Characteristics of the two sites where the effects of stump harvesting were studied. Climatic data are a mean for 1961–1990, and were taken from the official statistics from SMHI 2009.

	Karlsheda	Stadra
Site information		
Coordinates	57º N 15º E	59º N 14º E
Soil texture	sandy-loamy till	loamy till
Soil moisture	mesic	moist
Site index (H100)[1]	28	30
N concentration in soil (%)	0.29	0.08
C:N ratio	21	25
Regional climate		
Mean air temperature	5.5 ºC	4 ºC
Mean air temperature in Jan	–4 ºC	–2 ºC
Mean air temperature in July	15 ºC	15 ºC
Average precipitation	700 mm	700 mm
Snow cover	Nov–Apr	Nov–Apr
Growing season (daily mean >+5°C)	190 days	150–180 days
Forest Management		
Final harvest	Autumn 2007	Spring 2007
Removal of tops and branches	Spring 2008[2]	Aug 2007
Reference treatment	Undisturbed control (C)	Mounding (M)
Date of stump harvest	26–30 May 2008	Sep–Oct 2007

[1]Top height, height of the largest trees, m, at 100 years
[2]Tops and branches were not harvested from one control (C) and one stump-harvested (SH) plot. About one-third of branches and tops were left after harvest from the other plots.

2.2 Treatments and Experimental Design

On each clearfelled area, plots 50×50 m were laid out in a randomised block design, with two treatments: stump harvesting (SH) and reference. Each treatment was replicated three times, with the exception of the reference plots at Karlsheda, where only two reference plots were laid out. The reference plots at Karlsheda were undisturbed control plots (C). Since traditional forest management includes site preparation to facilitate the establishment of a new stand, mounding (M) was performed on the reference plots at Stadra.

Stumps were removed by means of an excavator with a Pallari stump-head. Stumps were first lifted and then shaken to leave as much soil as possible at the site. Finally, stumps were split and left to dry in small heaps on the clearfelled area. The soil disturbance caused by SH was assumed to be a sufficient site-preparation method. Where the distance between appropriate planting sites was too great, a planting patch was made with the excavator used for SH. Mounding was performed with the same excavator on the same occasion.

2.3 Measurements

2.3.1 Soil-Surface CO_2 Flux

Soil-surface CO_2 flux (R_s) was measured with a portable soil-respiration system, consisting of an infra-red gas analyser (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 to correct the CO_2 concentration for humidity and air pressure. During a measurement, the respiration chamber was attached to a pre-installed collar (diameter 10 cm). Measurements were performed every 4.2 seconds during 80 seconds. The last 14 measurements were used for estimating soil-surface CO_2 flux, using a linear fit. To prevent differences caused by measurements at different times of day, soil-surface CO_2 flux was measured within a two-hour period on each block, i.e. the stump-harvested treatment and its control.

On each plot, 20 PVC collars were inserted about 1 cm into the soil, to keep them steady and in close contact with the ground. Depending on the thickness of the humus layer, collars of different height were used. The collars were installed in a systematic grid, where the first point was randomised in such a way that each point had the same probability of being chosen within each plot. Once inserted, the collars were left in place in the field throughout the year, except during the lifting of stumps, when they were removed. After stump removal, the collars were re-installed, in approximately the same location as before. There was almost no vegetation on the clearfelled areas at Karlsheda and Stadra. At Stadra, three of the 120 measurement points consisted of grass, leading to high dark respiration. Those points were not used in the analysis. The older the clearfelled area became, the more vegetation was re-established. The focus in this study is heterotrophic respiration, hence R_s measurements ceased in June 2009 when the vegetation began to re-establish.

Soil temperature (T_s) at 10 cm depth, and soil moisture (H_s) at 5 cm depth, were measured adjacent to each collar at the time of R_s measurements. Soil temperature was measured by a temperature sensor (STP-1, PP-systems, Hitchin, UK) connected to the portable soil respiration system, and H_s was measured with a ThetaProbe (ML2x, Delta-T, Cambridge, UK).

At Karlsheda, R_s, T_s and H_s were measured on each plot once a week before the treatment started, and in total six times during the first month after the treatment began. At Stadra, R_s, T_s and H_s were measured once a month during the growing season. Measurements there began in June 2007 (three months before the treatment started) and continued until September 2009.

2.3.2 Eddy-Covariance Measurements at Stadra

At Stadra, ecosystem CO_2 fluxes were measured continuously by eddy-covariance in the SH treatment. The measurement system consisted basically of a 3-dimensional CSAT-3 sonic anemometer (Campbell Scientific, Logan, Utah, USA) and an LI-7500 open-path infrared gas-analyser (LI-COR, Lincoln, Nebraska, USA), mounted at 2.2 m height above the surface of the clearfelled area. Data were sampled at 10 Hz by a CR-1000 data logger (Campbell Scientific, Logan, Utah, USA). The system was powered by an EFOY-1600 fuel cell (SFC, Brunnthal, Germany), supported by a solar panel. The system was remotely controlled by a GSM modem. Data were post-processed according to the Euroflux methodology (Aubinet et al. 2000), by calculating half-hourly average fluxes in a coordinate system aligned with the mean wind vector. Occasional gaps occurred due to precipitation and fuel-cell failures, and were filled by using a combination of non-linear light-response and temperature response functions that were determined for adjacent time periods.

2.3.3 Meteorological Measurements at Stadra

As an integral part of the flux system, meteorological variables were also measured and stored as 30-min averages. In particular, air temperature, T_S and H_S, and photosynthetically active radiation, were measured close to the flux system.

2.3.4 Classification of Soil Disturbance

The disturbance after SH and M was classified at each R_S measurement point by a subjective ocular method, as either 'intact' soil, 'mineral' soil, 'mixed' soil, 'humus on humus' or 'wheel ruts'. The soil-disturbance classes are defined in Table 2.

Table 2. Definition of the soil disturbance classes after stump harvest or mounding.

Disturbance class	Definition
Intact	Intact humus layer, no visible disturbance of soil profile
Mineral	No humus layer, the mineral soil is visible
Mixed	Mineral soil and/or humus have been mixed
Humus on humus	Humus had been put on top of the humus layer
Wheel ruts	Clearly visible wheel ruts

2.4 Data Analysis

Measurements of R_S were first corrected for differences in the volume of chambers, caused by differences in the height of collars. Because R_S at both sites and T_S at Stadra did not meet the criteria of normal distribution and equal variance for performing an analysis of variance, these variables were logarithmically transformed (natural logarithm) before statistical analysis. For each site, treatment effects on $\ln(R_S)$, $\ln(T_S)$ (Stadra), T_S (Karlsheda) and H_S were tested by analysis of variance, using Proc mixed in SAS Statistical software (V9.1, SAS Institute, Cary, NC, USA). First, a simple model was used, including treatment, date and the covariate 'treatment·date' as fixed effects. The aim was to test if there was any treatment effect of SH compared to M. In the second model, where the effect of different soil disturbance was investigated, the model also included 'soil disturbance class', and the covariates 'treatment·date' and 'treatment·soil disturbance class' as fixed effects. Block and 'block·treatment' were random effects. Since R_S, T_S and H_S were measured on the same plots, the measurements could not be assumed to be independent, and date was used as a repeated measurement. If a fixed effect was significant, a paired *t*-test was used to indentify where a significant difference was obtained between treatments or between different soil-disturbance classes. A difference was assumed to be significant if $p \leq 0.05$.

3 Results

3.1 Karlsheda

The study at Karlsheda was performed during May and June 2008. Both months were very dry, and total precipitation during the period was only 19.5 mm. From 21 May until 4 June H_S decreased and T_S increased (Fig. 1). Thereafter, H_S and T_S remained rather constant. The measurements in May, before stump extraction had occurred, showed no differences between the plots, neither in T_S and H_S, nor in R_S (Fig. 1).

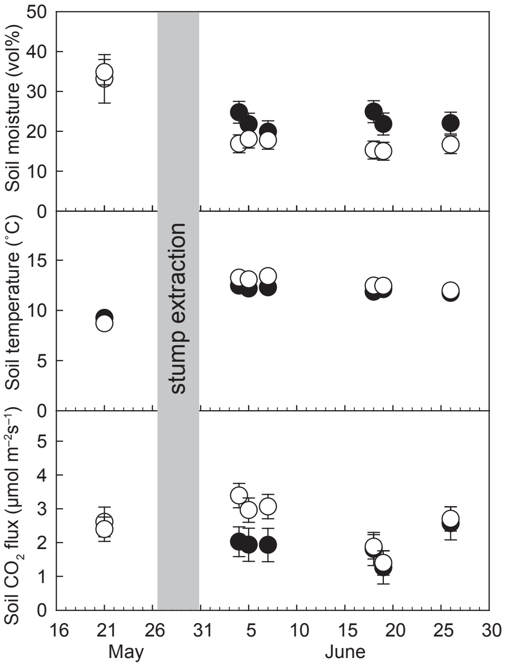

Fig 1. Soil moisture, soil temperature and soil-surface CO_2 flux in stump-harvested plots (SH, open circles) and control plots (C, filled circles) at Karlsheda in South Sweden. The first measurement in May occurred before the stump harvest had taken place. An error bar denotes a standard error (*n*=3 and 2 on SH plots and C plots, respectively.

3.1.1 Effects of SH

The statistical analysis using the Mixed model showed that treatment was a significant fixed effect for T_S and H_S at Karlsheda (Table 3). For $\ln(R_S)$, the covariate treatment·date was significant. Soil CO_2 flux increased directly following SH at Karlsheda (Fig. 1). The mean values were 3.1 and 2.0 µmol $m^{-2} \cdot s^{-1}$ for SH and C, respectively, during the first one–two weeks at Karlsheda. Stump harvest thus caused on average 60% more emission of soil CO_2, compared with the C plots. The difference between treatments had disappeared in the second half of June.

Depending on date, T_S was 0.3–1.3°C higher on SH compared to C (Fig. 1). The difference was significant for all occasions except the last two in June. Soil moisture was consistently lower in SH plots in June, but the change was significant on 4, 18 and 19 June only.

Table 3. p-values from the tests of the fixed effects in the analysis of variance. The dependent variables are soil moisture (H_S), soil temperature (T_S), the logarithm of soil temperature ($\ln(T_S)$) and the logarithm of R_S ($\ln(R_S)$). The fixed effects are treatment (treat), date (date) and the covariate 'treatement·date' (treat·date).

Site	Parameter	Treat	Date	Treat·date
Karlsheda	H_S	0.034	0.622	0.136
	T_S	<.001	<.001	0.005
	$\ln(R_S)$	0.630	<.001	0.001
Stadra	H_S	0.108	<.001	0.020
	$\ln(T_S)$	0.085	<.001	0.285
	$\ln(R_S)$	0.747	<.001	0.504

3.1.2 Differences between Soil Disturbance Classes

In the SH plots in Karlsheda, 32% of the soil surface was classified as 'intact', 28% as 'mineral', 30% as 'mixed', and 10% as 'humus on humus'. The class 'wheel ruts' was absent.

The largest R_S were measured in disturbance class 'humus on humus' (Fig. 2, Table 3). They were on average twice those for 'intact' in SH plots. However, there were only six measurements for the 'humus on humus' disturbance class, and variation between different measurement points was very large, which caused a large standard error. There were no significant differences between the classes 'mixed' and 'intact' in SH plots. The lowest emissions were obtained from the soil disturbance class 'mineral' (Fig. 2, Table 3).

Values of R_S from the different soil disturbance classes were also compared with 'intact' soil on C plots (Table 3). The comparison showed that R_S for 'intact' on SH plots was higher than that on C plots. Despite the fact that there was no visible disturbance on 'intact' soil, disturbance of the soil caused by the removal of roots could have caused this increase. However, the difference was small or non-significant in the latter part of June.

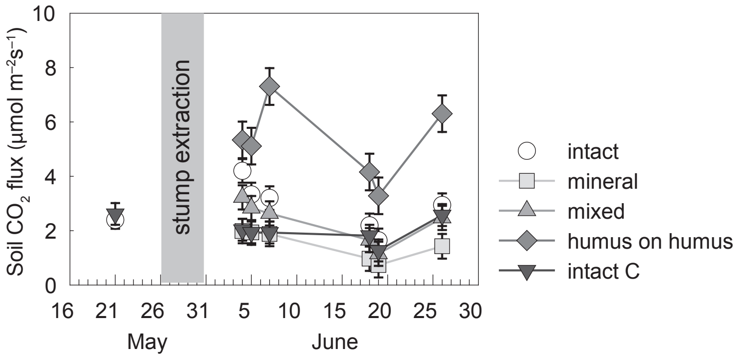

Fig. 2. Soil-surface CO_2 flux for different soil disturbance classes on a clear-felled area, on the stump-harvested (SH) plots compared to the undisturbed soil (intact C) on control plots at Karlsheda, South Sweden, in 2008. An error bar denotes a standard error. For further information about the soil disturbance class, see Table 2.

When the soil disturbance classes were used as base, H_s decreased mostly at points where SH resulted in 'humus on humus' (Table 3). The 'intact' soil on C plots was in general more moist than that in the soil disturbance classes 'intact' and 'mixed' on SH plots, but there was a significant difference for single dates only. Soil temperature was always significantly lower on the 'intact' soil on C plots at the beginning of June (Table 3). The highest T_s was found on the soil disturbance class 'humus on humus'. There was no significant difference in T_s between the different disturbance classes during the last two occasions in June.

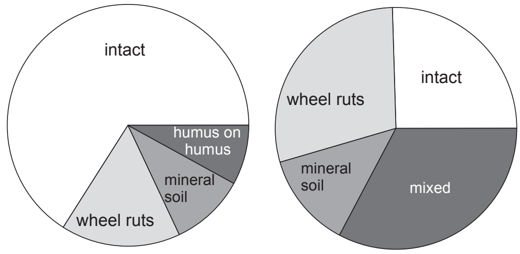

Fig. 3. Abundance of different soil-disturbance classes after mounding (left) and stump harvesting (right) at Stadra in 2008. For further information about the different classes, see Table 2.

3.2 Stadra

3.2.1 Abundance of Soil Disturbance

The winter before clear-felling in spring 2007 was unusually mild, and was followed by a rainy summer. The ground was very moist, both when the final harvest took place in spring and when SH and M took place in September. These wet conditions caused greater damage to the soil at Stadra than at Karlsheda.

The two treatments in the Stadra study caused different disturbances to the soil (Fig. 3). One-third of the soil surface was disturbed on the M plots. The disturbed part was rather evenly distributed between the three different soil disturbance classes 'humus on humus', 'mineral soil' and 'wheel ruts'. On SH plots, three-quarters of the area was dominated by disturbed soil (Fig. 3). The major disturbances were the soil disturbance class 'mixed' (1/3), followed by 'wheel ruts' (ca. 1/4). 'Mineral' soil covered ca. 1/6 of the soil surface, and was almost as abundant as on M plots.

Basal area, as measured on the stumps of the former stand, was 53 ±7 and 51 ±1 m^2 ha^{-1} on plots later subjected to SH and M, respectively. The stem density was also similar. The three preliminary measurements of soil R_S, T_s and H_s that were made in summer 2007, before SH and site preparation took place, did not reveal any differences (Fig. 4).

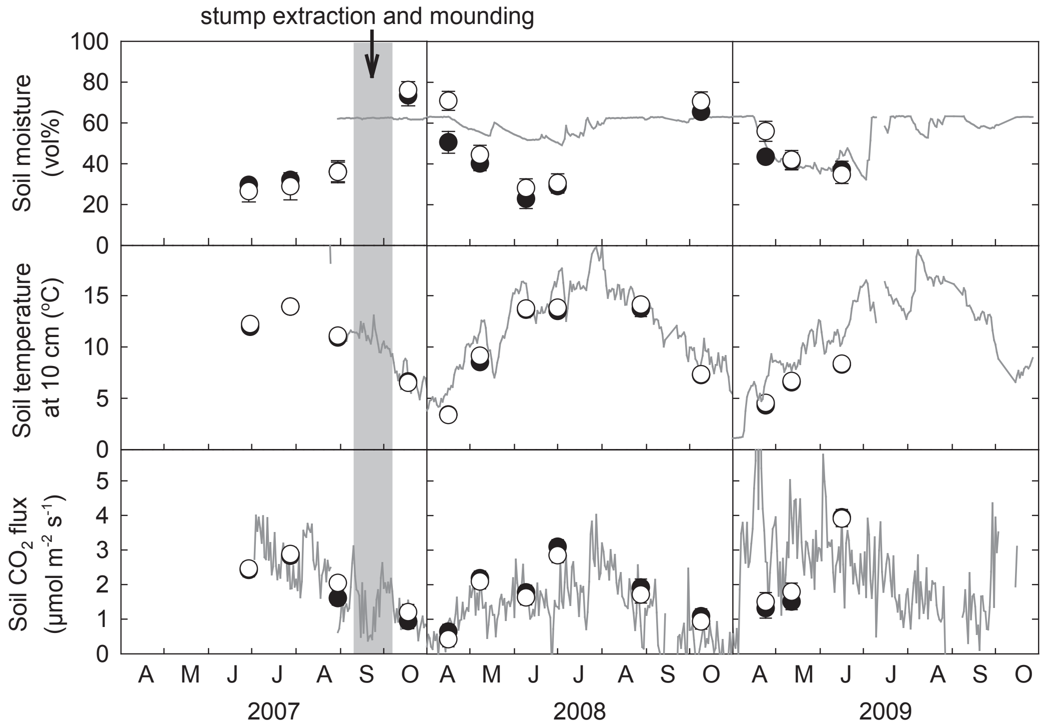

Fig. 4. Soil moisture, soil temperature and soil-surface CO_2 flux in stump-harvested plots (SH, open circles) and mounding plots (M, filled circles) at Stadra in 2007–2009. Time is shown in the X axis, where A, M, J, J, A, S and O denote the months from April to October. An error bar denotes a standard error (*n*=3). The grey lines show the values measured continuously by the eddy-covariance system and the meteorological sensors, respectively.

3.2.2 Seasonal Dynamics of R_s, T_s and H_s

Soil temperature followed a seasonal pattern, with low temperatures in spring and autumn, and higher temperatures during the summer months June–August (Fig. 4). Soil moisture had an opposite trend, with the highest values in autumn, with a mean of 69% of volume. Several places, especially on soil affected by 'wheel ruts', were flooded and had an open water surface. The lowest values of H_s occurred during the summer months June–August. The fluxes of ecosystem CO_2 measured continuously with the eddy-covariance system and the R_s were similar, with high values when the highest temperature occurred (Fig. 4). There was almost no ground vegetation during the first year after treatment; consequently, the CO_2 exchange was dominated by heterotrophic respiration. From June 2009, grasses (mainly *Deschampsia flexuosa* L.) had started to invade the clearfelled area. The influence of increasing ground vegetation on the carbon balance could be seen as increased photosynthesis, but also resulted in increased dark-respiration. After June 2009, only the ecosystem CO_2 flux measurements were continued.

3.2.3 Comparison between Treatments

The seasonal pattern of R_s, T_s and H_s in the two treatments was similar (Fig. 4). The covariate 'treatment date' was a significant fixed effect for H_s (Table 3). Stump harvested plots had significantly higher H_s in April 2008, but there were otherwise no significant differences. Between the treatments there was no significant difference in R_s, nor in T_s, on any occasion (Table 3).

Table 4. Means of soil moisture (H_s) and soil-surface CO_2 flux (R_s) for different soil disturbance classes in stump-harvested plots (SH) and mounding plots (M) at Stadra for the whole treatment period during 2007–2009. For further information about different soil disturbance classes, see Table 2. Means of R_s are based on log-transformed data. Different letters indicates a significant difference ($p \leq 0.05$) within each treatment based on pairwise t-tests.

Parameter	Treatment	Intact	Wheel ruts	Mineral	Mixed	Humus on humus
H_s	SH	44^{ac}	65^{b}	48^{a}	42^{c}	
(vol%)	M	45^{ab}	50^{a}	40^{b}		40^{b}
R_s	SH	1.7^{a}	1.4^{b}	1.5^{ab}	1.6^{a}	
(μmol m^{-2} s^{-1})	M	1.7^{a}	1.4^{b}	0.9^{c}		1.2^{b}

3.2.4 Comparison between Soil Disturbance Classes

The different classes of soil disturbances exhibited different levels of R_s (Table 4). The highest values occurred in the classes ‘intact’ and ‘mixed’ soil profiles. Emissions of CO_2 from areas of ‘wheel ruts’ were significantly lower than those from the ‘intact’ soil profile on both SH and M plots. The emissions were also significantly lower in ‘mineral’ soil than in the ‘intact’ soil on M plots, but there was no significant difference between these soil disturbance classes on SH plots. Soil moisture was on average ca. 20%-units higher after treatment for soils with ‘wheel ruts’ on SH plots, compared to intact soil on both SH and M plots ($p \leq 0.001$). Otherwise, there were no significant differences between ‘intact’ soil and any other soil disturbance class within each treatment (Table 4).

The different soil disturbance classes were also compared between the treatments in Stadra. There was no significant difference between SH and M plots, neither in R_s nor in H_s, of ‘intact’ soil profiles. However, R_s of ‘mineral’ soil from SH plots was significantly higher than from M plots. The soil disturbance classes ‘wheel ruts’ and ‘mineral’ also showed a significantly higher H_s on SH compared to M.

4 Discussion

4.1 Treatment Effect on R_s

The measurements at Karlsheda showed, as a direct response to SH, an increased R_s during the first three measurements. The increase was a result of higher emissions from areas classified as ‘mixed’ and ‘humus on humus’, as well as from ‘intact’. The R_s of the latter areas increased, compared to ‘intact’ soil in C plots (see Fig. 2). It may be explained by a disturbance within the soil when stumps and roots were lifted away, even though no disturbances could be seen from the top of the soil. The results from Karlsheda support the hypothesis, that soil mixing increases decomposition of soil organic matter. The effect was, however, not long-lasting. It was absent already after a few weeks, and in the two-year study at Stadra, SH did not affect R_s more than M, neither a few weeks after SH, nor during subsequent years. There could have been an initial flush, but SH at Stadra occurred in autumn when R_s already was very low; consequently, any change is more difficult to detect. However, a temporary increase could have occurred between two measurements of R_s with the portable system. We conclude from those two studies that SH affected R_s more than M only in the very early phase (weeks), and not in the subsequent period of 1–2 years.

The conclusions are valid only if the assumptions about R_s stated in the Introduction are correct. One assumption was that R_s was dominated by heterotrophic respiration, and that the autotrophic part was negligible. Since the vegetation during the studied period was very sparse, and since the measurements obtained by the eddy-covariance system did not show any obvious CO_2 uptake by plants during daytime, this may be a correct assumption. However, during the second year, no vegetation was visible in April and May, but in June it began to recover and in August the area was covered by *Dechampsia flexuosa*. The high respiration values in June 2009 may therefore be caused by vegetation. The conclusion would also be correct if the autotrophic respiration were of the same size in both treatments. In August 2009, the ground vegetation was harvested on all plots at Stadra. There was no difference between treatments, suggesting that the autotrophic respiration would be of similar magnitude in the two treatments. Another assumption was that CO_2 evolution from fresh roots and stumps was negligible during this first phase. If this was not correct, the minor amount of fresh roots and stumps on SH plots would counteract the factor of soil disturbance. At Stadra, stumps and root systems corresponding to 1.9 kg C m^{-2} were harvested in the SH treatments (data not published). If roots and stumps decompose as described by Hyvönen and Ågren (2001), about 6 g C m^{-2} and 16 g C m^{-2} would be released from this pool in the first and second year, respectively. This corresponds to a flux of about 0.05 and 0.13 mmol CO_2 m^{-2} s^{-1} during the summer period of the first and the second year, respectively, given that decomposition of this pool follows the same annual pattern as R_s measured by the eddy-covariance system. The size of these fluxes is minor, and would not affect the conclusions of the study (cf. Figs. 2 and 4).

4.2 Soil Disturbance

The area of disturbed soil after SH was about 70% at Karlsheda and Stadra, which is of the same magnitude as in a study by Kardell (1992), which included nine SH sites throughout Sweden.

'Wheel ruts' were not common at Karlsheda, but abundant at Stadra. One reason for this is that the soil was moister and contained finer material at Stadra (Table 1), which made it more sensitive to harvesting damage. The wet conditions at Stadra, first during the clear-felling of the stand, then during SH and M, caused severe damage to the soil by the wheels of the harvesting machines. Branches and tops were also removed, and could consequently not be used to increase the resilience of the soil of the strip road beneath the forwarder and caterpillar. Other reasons for the absence of 'wheel ruts' at Karlsheda are that more forest residues were left on-site, and branches were laid on the strip road to prevent soil damage. Soil damage existed in both treatments at Stadra, but when stumps with their associated coarse roots disappeared after stump extraction, the resilience of the soil further decreased. This could explain why damage almost doubled on SH plots, compared to M plots.

Compaction caused by SH was also observed in an experiment in northern Idaho by Page-Dumroese et al. (1998). In compacted soil, the availability of oxygen needed for aerobic decomposition is limited, but compaction also causes depressions where water can be retained. These effects have a counteractive effect on R_s. It was clearly shown that compacted areas at Stadra, such as 'wheel ruts', had lower R_s as compared to 'intact' or 'mixed' soil. Even though compaction decreased CO_2 emissions, it can lead to other adverse effects, such as emission of the more potent greenhouse gases N_2O and CH_4. Compaction will also limit the ability of living roots to penetrate the soil, which in the longer term can decrease plant growth (Page-Dumroese et al. 1998). To prevent severe damage to soil, caution must be exercised during forestry operations carried out in unfavourable weather and soil conditions. Here, common trends towards higher soil moisture after harvest, due to the loss of evapotranspiration, have also to be taken into account. The soil at Stadra was classified as mesic in the mature forest, but became moist in the final clearfelled area.

4.3 Comparison with Site Preparation

Our study suggests that the effect of SH on CO_2 flux is small or absent compared to that of site preparation such as M. The most common method of site preparation currently employed in Sweden is, however, harrowing. Harrowing affects a larger proportion of the soil surface than does M. In reviews of various site preparation studies, more intensive site preparation had been concluded to lead to greater losses of soil carbon (Johnson 1992, Freeman et al. 2005, Jandl et al. 2007); harrowing may therefore have a larger effect than M on soil carbon. However, other studies did not observe any long-term effects of different site preparation methods on soil carbon (e.g. Nordborg 2001).

In the long term, forest growth is important for the recovery of soil carbon after a final harvest (Freeman et al. 2005, Jandl et al. 2007). Site preparation leads to more rapid plant establishment, in response to reduced competition from vegetation (e.g. Nilsson and Örlander 1999, Mattsson and Bergsten 2003); and increased decomposition, which will increase nutrient availability (Jandl et al. 2007). Other reasons are the increased infiltration of water, increased soil temperature, which leads to a lower risk of frost damage, and better root development (Örlander et al. 1998, Ross and Malcolm 1982), as well as a reduced risk of damage by pests (Örlander and Nilsson 1999). On the other hand, stump removal increases the risk for compaction of soil, which can limit root development, therefore plant growth (Page-Dumroese et al. 1998). How efficient SH is as a site preparation method, and the risk for soil compaction, calls for further study, to determine its long-term effects on the soil carbon pool.

4.4 Carbon Neutrality of Stumps for Energy

To obtain a comprehensive view of how 'carbon-neutral' stumps are as a source of energy, one should also take into account the decrease of the carbon pool stored in stumps and coarse roots in the forest. The CO_2 that would have been emitted slowly from decaying stumps in the forest, will instead be emitted by combustion about one or two years after harvest. The time required to obtain a 50% loss of stump mass in Swedish forests is about 14 years (Melin et al. 2009, cf. Palviainen et al. 2010). Since this pool decreases with time, the temporal perspective is important when dealing with how well stumps used for energy perform in mitigating climate change. Other factors must also be taken into account, such as the energy required for harvesting, transporting and preparing the stumps for their final use. In a recent life-cycle assessment of SH, Lindholm (2010) concludes that great savings in greenhouse gas emissions were obtained by substituting stumps for fossil fuel. The longer was the time perspective, the greater were the savings. Lindholm's study did not, however, take into account any effect of increased soil respiration caused by SH. Our study shows that this effect is small compared to that of ordinary site preparation during the early years. There is, however, a need to study more sites under different conditions, to obtain a more representative answer, and to follow the long-term effect on the soil carbon pool.

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References

Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., Kowalski, A.S., Martin, P.H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grunwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R. & Vesala, T. 2000. Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology. Advances in Ecological Research 30: 113–175.

Berg, B., Ekbohm, G. & McClaugherty, C. 1984. Lignin and holocellulose relations during long-term decomposition of some forest litters. Long-term decomposition in a Scots pine forest. IV. Canadian Journal of Botany 62: 2540–2550.

Egnell, G., Hyvönen, R., Högbom, L., Johansson, T., Lundmark, T., Olsson, B., Ring, E. & von Sydow, F. 2007. Miljökonsekvenser av stubbskörd – en sammanställning av kunskap och kunskapsbehov. [Environmental aspects on stump-harvest – compilation of knowledge and knowledge gaps]. Eskilstuna: Statens Energimyndighet. Rapport ER 2007:40. 116 p. (In Swedish, English summary). ISSN 1403-1892.

EU 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (1). Official Journal of the European Union L140: 16–62.

Freeman, M., Morén, A.S., Strömgren, M. & Linder, S. 2005. Climate change impacts on forests in Europe: biological impact mechanisms. In: Kellomäki, S. & Leinonen S. (eds.). Management of European forests under changing climatic conditions. Research Notes 163. Joensuu, Finland: Forest Faculty, University of Joensuu. p 46–115.

Harmon, M.E., Franklin, J.F., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P. Aumen, N.G. & Cummins, K.W. 1986. Ecology of coarse woody debris in temperate ecosystems. In: McFayden, A. & Ford, E.D. (ed.). Advances in Ecological Research 15. Academic press London. p. 133–302.

Hope, G.D. 2007. Changes in soil properties, tree growth, and nutrition over a period of 10 years after stump removal and scarification on moderately coarse soils in interior British Columbia. Forest Ecology and Management 242: 625–635.

Hyvönen, R. & Ågren, G. 2001. Decomposer invasion rate, decomposer growth rate, and substrate chemical quality: how they influence soil organic matter turnover. Canadian Journal of Forest Research 31: 1594–1601.

— , Ågren, G.I., Linder S., Persson, T., Cotrufo, M.F., Ekblad, A., Freeman, M., Grelle, A., Janssens I.A., Jarvis, P.G., Kellomäki, S., Lindroth, A., Loustau, D., Lundmark, T., Norby, R.J., Oren, R., Pilegaard, K., Ryan, M.G., Sigurdsson, B.D., Strömgren, M., van Oijen, M. & Wallin, G. 2007. The likely impact of elevated [CO_2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. New Phytologist 173: 463–480.

Hyvönen-Olsson, R. & Grelle, A. 2007. Effekter på skogens kolbalans. In: Egnell, G., Hyvönen, R., Högbom, L., Johansson, T., Lundmark, T., Olsson, B., Ring, E. & von Sydow, F. (eds). Miljökonsekvenser av stubbskörd – en sammanställning av kunskap och kunskapsbehov. [Environmental aspects on stump-harvest – compilation of knowledge and knowledge gaps]. Eskilstuna: Statens Energimyndighet. Rapport ER 2007:40. 116 p. (In Swedish, English summary) ISSN 1403-1892. p. 89–102.

Houghton, J.T., Ding Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K. & Johnson, C.A. 2001. Climate change 2001: the scientific basis. Contribution of working group I to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge university press, Cambridge, UK. 944 p.

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K. & Byrne, K.A. 2007. Review. How strongly can forest management influence soil carbon sequestration? Geoderma 137: 253–268.

Johansson, M.-B. 1994. The influence of soil scarification on the turn-over rate of slash needles and nutrient release. *Scandinavian Journal* of Forest Research 9: 170–179.

Johnson, D.W. 1992. Effects of forest management on soil carbon storage. Water, Air, and Soil Pollution 64: 83–120.

— & Curtis, P.S. 2001. Effects of forest management on soil C and N storage: meta analysis. Forest Ecology and Management 140: 227–238.

Kardell, L. 1992. Vegetationsförändring, plantetablering samt bärproduktion efter stubb- och ristäkt. Rapport 50. Inst. för skoglig landskapsvård, Sveriges lantbruksuniversitet. ISRN SLU-SLV-R-50-SE. (In Swedish).

Lindholm, E.-L. 2010. Energy use and environmental impact of roundwood and forest fuel production in Sweden. Doctoral thesis no 2010:40. Faculty of Natural Resources and Agricultural Sciences, Swedish University of Agricultural Sciences. ISBN 978-91-576-7453-1.

Lundmark-Thelin, A. & Johansson, M.-B. 1997. Influence of mechanical site preparation on decomposition and nutrient dynamics of Norway spruce (Picea abies (L.) Karst) needle litter and slash needles. Forest Ecology and Management 96: 101–110.

Mallik, A. & Hu, D. 1997. Soil respiration following site preparation treatments in boreal mixedwood forest. Forest Ecology and Management 97: 265–275.

Marklund, L.G. 1988. Biomassafunktioner for tall, gran och björk i Sverige [Biomass functions for pine, spruce and birch in Sweden]. Department of Forest Survey. Report 45. Swedish University of Agricultural Sciences, Umeå. 73 p. (In Swedish). ISBN 91-576-3524-2.

Mattsson, S. & Bergsten, U. 2003. Pinus contorta growth in northern Sweden as affected by soil scarification. New Forests 26: 217–231.

McLaughlin, J.W., Gale, M.R., Jurgensen, M.F. & Trettin, C.C. 2000. Soil organic matter and nitrogen cycling in response to harvesting, mechanical site preparation, and fertilisation in a wetland with a mineral substrate. Forest Ecology and Management 129: 7–23.

Melin, Y., Petersson, H. & Nordfjell, T. 2009. Decomposition of stump and root systems of Norway spruce in Sweden – a modeling approach. Forest Ecology and Management 257: 1445–1451.

Nilsson U. & Örlander, G. 1999. Vegetation management on grass dominated clearcuts in southern Sweden. Canadian Journal of forest research 29: 1015–1026.

Nordborg, F. 2001. Effects of site preparation on site properties and on growth, damage and nitrogen uptake in planted seedlings. PhD-thesis. Acta Universitatis Agriculturae Sueciae, Silvestria 195. 24 p.

— , Nilsson, U., Gemmel, P. & Örlander, G. 2006. Carbon and nitrogen stocks in soil, trees and field vegetation in conifer plantations 10 years after deep soil cultivation and patch scarification. Scandinavian Journal of Forest Research. 21: 356–363.

Örlander, G. & Nilsson, U. 1999. Effect of reforestation methods on pine weevil (Hylobius abietis) damage and seedling survival. Scandinavian Journal of Forest Research 14: 341–354.

— , Egnell, G. & Albrektsson, A. 1996. Long-term effects of site preparation on growth in Scots pine. Forest Ecology and Management 86: 27–37.

— , Hallsby, G., Gemmel, P. & Wilhelmsson, C. 1998. Inverting improves establishment of Pinus contorta and Picea abies – 10-year results from a site preparation trial in northern Sweden. Scandinavian Journal of Forest Research 13: 160–168.

Page-Dumreose, D., Harvey, A.E. Jurgensen, M.F. & Amaranthus, M.P. 1998. Impacts of soil compaction and tree stump removal on soil properties and outplanted seedlings in northern Idaho, USA. Canadian Journal of Forest Research 78: 29–34.

Palviainen, M., Finér, L., Laiho, R., Shorohova, E., Kapitsa, E. & Vanha-Majamaa, I. 2010. Carbon and nitrogen release from decomposing Scots pine, Norway spruce and silver birch stumps. Forest Ecology and Management 259(3): 390–398.

Parkinson, K.J. 1981. An improved method for measuring soil respiration in the field. The Journal of Applied Ecology 18: 221–228.

Prescott, C.E., Blevins, L.L & Stanley, C.L. 2000. Effects of clear-cutting on decomposition rate of litter and forest floor in forests of British Columbia. Canadian Journal of Forest Research 30: 1751–1757.

Pumpanen, J., Westman, C.J. & Ilvesniemi, H. 2004. Soil CO_2 efflux from a podzolic forest soil before and after forest clear-cutting and site preparation. Boreal Environment Research 9: 199–212.

Ross, S.M. & Malcolm, D.C. 1982. Effects of intensive forest cultivation practices on upland heath soils in south-east Scotland. Forestry 55: 155–171.

Schmidt, M., Macdonald, S. & Rothwell, R. 1996. Impacts of harvesting and mechanical site preparation on soil chemical properties of mixed-wood boreal forest sites in Alberta. Canadian Journal of Soil Science 76: 531–540.

SMHI. 2009. [Internet site] Available at: http:www.smhi..se. [Cited 25 Oct 2009].

Walmsley, J.D. & Godbold, D.L. 2010. Stump harvesting for bioenergy – a review of the environmental impacts. Forestry 83(1): 17–38.

Zabowski, D., Chambreau, D., Rotramel, N. & Thies, W.G. 2008. Long-term effects of stump removal to control root rot on forest soil bulk density, soil carbon and nitrogen content. Forest Ecology and Management 255: 720–727.

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