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Soil CO_2 efflux from a podzolic forest soil before and after forest clear-cutting and site preparation

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The effect of forest harvesting and subsequent site preparation on soil CO_2 efflux was studied on a clear-cut site with five soil treatments, including mounding, exposed E- and C-horizons, and undisturbed soil with and without logging residue left on soil. Site preparation accounted for over 75% of the total variance in soil CO_2 effluxes. Clear-cutting and removal of logging residue decreased instantaneous CO_2 effluxes from the soil surface by 40%, whereas the highest instantaneous effluxes were measured from mounds and from undisturbed soil with logging residue. These sampling points showed effluxes twice as high as those in the control forest or in places where the logging residue was removed. The lowest instantaneous effluxes, about 18% of those in the control forest, were measured from the exposed C-horizon. Annual effluxes in the forest were 1900 g CO_2 m^{-2} before harvesting and 3242, 2845, and 2926 g m^{-2} in the three successive years after harvesting in places with logging residue, but when logging residue was removed, the annual efflux decreased to pre clear-cutting levels. Annual CO_2 efflux from the logging residue was 1423 g m^{-2} during the first year after clear-cutting equaling 388 g m^{-2} of C assuming even distribution of logging residue on the site. Thus, some 23% of the total C pool in the above-ground logging residue was released during the first year after clear-cutting. The estimated annual C emissions from the O-, E- and B-horizons were 352 g m^{-2} during the first year after clear-cutting. Assuming that this compounded emission originated from the decomposition of roots, this would make about 20% of measured root biomass on the site. The decomposition rate was also fastest during this period, slowing in subsequent years. Based on the measured CO_2 evolution rate, the reduction observed in the decomposition rate, and the aging of decomposing material, we believe that the decomposition of logging residue is a slow process. Consequently substantial amounts of non-decomposed material still may remain at the time point when the developing new forest starts to function as a carbon sink. The carbon pool of the soil may therefore increase in the long run as a result of intensive forest management.

Introduction

Carbon accumulation in forest soils is an important part of the carbon pool of terrestrial ecosystems; half of the world's nonfossil carbon is in forest biomes, and boreal forests are the largest single terrestrial carbon pool, estimated to contain approximately 15% of the C storage in soils worldwide (Schlesinger 1977, Post *et al*. 1982).

The carbon pool of soil is regulated by the balance between above-ground and below-ground production of plant litter, and the decomposition of that material by soil microorganisms. Forest disturbances such as fire, wind-throw, and forest harvesting, affect this balance, and consequently, the amount of CO_2 released from the soil (Gordon *et al*. 1987, Millikin *et al*. 1996, Nakane *et al*. 1996, Lytle and Cronan 1998). Upon forest harvest, a larger amount of organic matter reaches the soil as compared with the annual litter input. At the same time, the flow of rhizosphere exudates and the annual litter input are reduced, remaining low until a new tree stand has developed. The amount of carbon released into the atmosphere from decomposition is greater than that from the litter input of ground vegetation during the first years following the harvesting (Covington 1981). Further, when the tree canopy is removed, soil temperature and water content increase (Bormann *et al*. 1974, Toland and Zak 1994), favoring biological activity (Gadgil and Gadgil 1978), which results in enhanced organic matter decomposition. The effect on the soil carbon stock is the net effect of the increased decomposition rate and the amount of organic matter added to the soil as logging residue. However, the net effect of clear-cutting on soil CO_2 efflux and on the carbon pool of the soil is ambiguous. Simultaneously with the increased decomposition of litter material, the amount of root and rhizosphere respiration decreases (Bowden *et al*. 1993, Nakane *et al*. 1996, Boone *et al*. 1998, Buchmann 2000). The short-term effects of forest harvesting on soil CO_2 efflux are not well known, with existing studies showing contradictory results. Ewel *et al*. (1987a), Gordon *et al*. (1987), and Lytle and Cronan (1998) reported higher soil CO_2 efflux after harvesting, whereas Edwards and Ross-Todd (1983) and Nakane *et al*. (1996) found the opposite. According to Fernandez *et al*. (1993), no changes in soil CO_2 efflux occurred after harvesting.

Site preparation is commonly used in forestry; in Finland, on average, 122 300 hectares were annually treated between 1995 and 2000 (Finnish Statistical Yearbook of Forestry 2001) to promote the germination of seeds and seedling growth and to facilitate the survival of planted tree seedlings during the first years after harvesting. In site preparation, the organic surface layer of the soil is partially mixed with mineral soil material, and mineral soil is exposed to various depths. The preparation affects the temperature and water conditions of the soil surface layers by creating mounds of soil and shaded pits which have a different microclimate and organic matter distribution than that of undisturbed soil (Beatty and Stone 1986, McClellan *et al*. 1990, Millikin 1996). Because soil organic matter decomposition is controlled by temperature, moisture, and soil organic matter quality, all of which are highly variable, soil CO_2 efflux from different microsites can be highly variable as well (Davidson *et al*. 1998). The effect of soil disturbance on CO_2 efflux remains, however, obscure. Such information is essential in estimating the carbon emissions caused by different forest management procedures.

The aim of this study was to quantify the effect of forest harvest by clear-cutting and consequent site preparation on CO_2 efflux from a boreal forest soil. We assumed that the harvesting of trees increases CO_2 emissions from the soil, as compared with that from an intact forest, since in clear-cutting a large amount of dead organic matter is released on the soil surface. To test this hypothesis, we monitored the CO_2 efflux from a clear-cut site and from an adjacent uncut forest over a three-year period following the clear-cutting. We also studied how site preparation affected soil CO_2 efflux by exposing the soil surface of the clear-cut site to different site preparation methods. Finally, we evaluated what is the role of logging residue on soil carbon balance after clear-cutting.

Materials and methods

Site description

The study site was located in a 130-year-old Scots pine–Norway spruce stand in southern Finland (61°48´N, 24°19´E, 151–153 m a.s.l.). A 100-meter-long catena, which covers a gradient from dry to mesic, was chosen for the study. The tree stand was dominated by Scots pine (*Pinus* *sylvestris* L.) at the dry end of the catena, and by Norway spruce (*Picea abies* (L.) Karst.) at the mesic end. The ground vegetation consisted mainly of the shrubs *Vaccinium vitis-idaea* L. and *V. myrtillus* L., with some *Oxalis acetosella* L. in the mesic part of the site. The forest floor was covered with mosses (*Dicranum polysetum* Sw., *Pleurozium schereberi* (Brid.) Mitt., and *Hylocomium splendens* (Hedw.) Schimp.). The above-ground biomass of the forest ranged from 13.7 to 16.3 kg m^{-2} at the dry and mesic sites, respectively.

The parent material of the soil at the site is a glaciofluvial deposit, with a texture varying from coarse to fine sand. According to the FAO-Unesco soil classification system, the soil is a haplic podzol (FAO-Unesco 1990). The physical, chemical, and biological soil properties have been described in detail by Mecke and Ilvesniemi (1999) and Pietikäinen *et al.* (1999). Carbon concentration in undisturbed forest soil ranged from 48.6% in the organic horizon to 0.12% in the C-horizon soil. The corresponding soil pH ($CaCl_2$) values are 2.79 and 5.23 (Pietikäinen *et al.* 1999). The bedrock lies at a depth of 8–10 m and is mainly acidic granite, granodiorite, and mica-gneiss, with some small intrusions of gabbro and peridotite. The annual precipitation averages 709 mm and the annual mean temperature of the area is 2.9 °C; January is the coldest month (mean –8.9 °C) and July the warmest (mean 15.3 °C) (Finnish Meteorological Institute 1991).

Experimental design and measurements

Closed static chambers (diameter 0.20 m, height 0.30 m) were used for measuring the CO_2 effluxes. The chambers were attached to plastic collars (diameter 0.20 m, height 0.05 m), which were permanently installed in the soil. The lower edge of the collar was pushed to a depth of about 0.05 m from the surface of the moss layer. Living plants were not removed from the collars.

The chambers were equipped with a fan to mix the headspace air and were covered with aluminum foil to shut out sunlight. Gas samples (50 cm^3, 0.9% of the chamber headspace) were taken manually 0, 2, 6, and 10 min after the chamber closure with polyethylene syringes (BD Plastipak 60, BOC Ohmeda, Helsingborg, Sweden) equipped with a three-way valve (BD Connecta™ Stopcock, Becton Dickinson, NJ, USA). The CO_2 concentration of the gas samples was determined within 6 h with an infrared gas analyzer (URAS 3G, Hartmann & Braun, Frankfurt am Main, Germany). The CO_2 efflux from soil was calculated from the increase in CO_2 concentration within the chamber air.

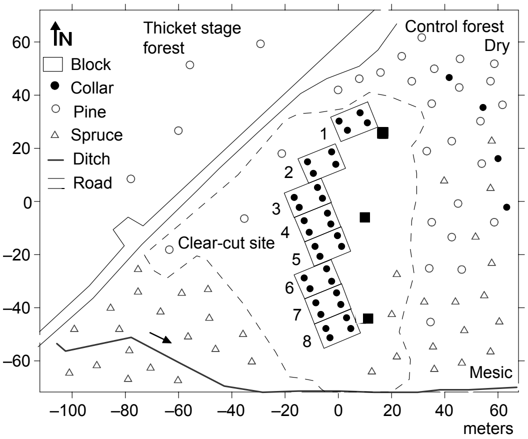

Fig. 1. Map of the experimental site. The site was located on a south-facing gentle slope with a moisture gradient from dry to mesic soil. Soil CO_2 was measured with closed static chambers from three collars (■) installed in the soil in June 1997 before the clear-cut and from 32 collars (•) installed in June 1998 after the clear-cut on eight blocks along the moisture gradient. In each block, soil was treated with four different site preparation methods. For comparison, we also installed four collars (•) for control measurements in an adjacent non-cut forest in June 1998.

From June 1997 onwards, soil CO_2 efflux was measured weekly (mornings between 8:00 and 11:00) from three collars in the standing forest (black rectangles in Fig. 1). The forest was clear-cut in February 1998. After clear-cutting, we removed logging residue from the three collars and continued CO_2 efflux measurements biweekly in the summers of 1998 and 1999. In May 1998, we established eight 10 m × 15 m blocks at the clear-cut site to study forest regeneration after site preparation (de Chantal *et al.* 2003). In each block, we established sampling points with four different soil treatments (Fig. 1). For simulating mounding and harrowing, the organic layer (O-horizon) on top of the soil and the uppermost 0.2 m of the mineral soil were excavated and placed upside-down next to the

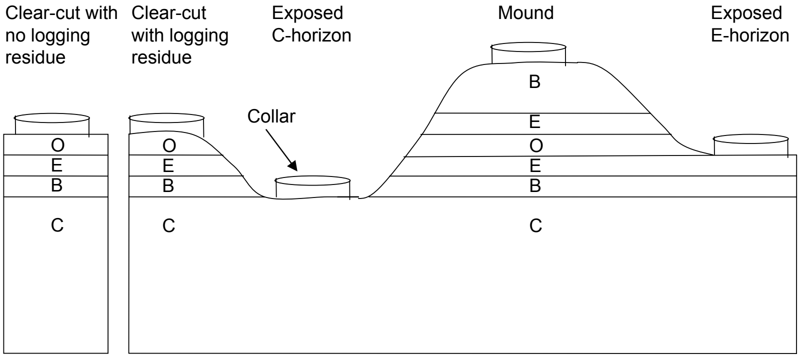

Fig. 2. Schematic figure of site preparations used in the experiment. After the clear-cut, eight blocks in which soil was treated with four different methods to simulate site preparation were established. Soil treatments on each block included "clear-cut with logging residue", where the logging residue of harvested trees was left on the site; "exposed C-horizon", where the O-horizon and the surface of the mineral soil were removed; "exposed E-horizon", where the O-horizon was removed; and "mound", where the mineral and organic soils were mixed. Plastic collars were installed permanently in all blocks and in the control forest in June 1998. Three long-term monitoring collars were installed at the site in June 1997 before the clear-cut, and the logging residue of harvested trees was removed from them immediately after the clear-cut.

excavated pit (Fig. 2). A mound was formed with the B-horizon on top, followed by the eluvial layer (E-horizon) and the organic layer inside. Next to the mound, soil was exposed down to the C-horizon, above which most of the roots were confined. The two other treatments were exposed E-horizon, where the O-horizon lying on the mineral soil was removed and clear-cut without site preparation, and removal of the logging residue, where the soil was left undisturbed and the litter of the harvested trees remained in place. To study the internal variation of CO_2 efflux within the site, we installed collars on each site preparation, altogether 32 collars in eight blocks. For comparison, we installed an additional four collars in intact forest soil at the dry end of the moisture gradient in the adjacent uncut forest in June 1998. The total number of collars used in the experiment was therefore 39 (Fig. 1).

In the summers of 1998 and 1999, we then studied the seasonal patterns in soil CO_2 efflux from all treatments by sampling biweekly all collars of blocks 1 and 8, the three collars measured since 1997, and four additional collars installed in the control forest (Fig. 1 and Table 1). An intensive sampling where all of the 39 collars were measured for studying the internal variation within the site was done twice in the summer of 1998 and three times in the summers of 1999 and 2000.

Soil temperature at a depth of 0.03 m in O-horizon soil was measured in each collar immediately after the CO_2 efflux measurement with a temperature probe connected to a portable electronic thermometer (Fluke 52/KJ, Fluke Electronics, Everett, WA, USA). In places where the O-horizon was removed, the temperatures were measured at a depth of about 0.01 m in the mineral soil. We also measured soil temperature on an hourly basis in places where logging residue was removed in the humus layer and in the mineral soil at depths of 0, 0.05, 0.15, and 0.50 m using thermocouples connected to a data logger (Delta-T, Delta-T Devices Ltd, Cambridge, UK). Soil matric potential was measured at respective depths by tensiometers (Soil Measurement Systems, TX, USA) and a Tensicorder (Soil Measurement Systems, TX, USA).

The amount of logging residue released on the site in clear-cutting was derived from biomass estimates for stems, branches, foliage, stumps, and roots. The branches with needles from 17 spruce and 7 pine trees were weighed fresh. A sample of branches from separate trees was used to determine the biomass fresh weight dry weight ratio, and an allometric function between DBH (diameter at a breast height of 1.3 m) and the amount of logging residue was established. The biomass of the logging residue at the site was calculated with this allometric function using the DBH measured from all trees removed in clear-cutting. Fine root biomass was estimated to a depth of 0.6 m from 72 core samples. These core samples were taken before clear-cutting. The biomass of coarse roots and stumps was measured from four sample trees, and a function between DBH and root dry biomass was established and used to determine the proportion of coarse roots and stumps at the clear-cut area. Carbon content in all biomass compartments was assumed to be 52%.

Calculations and statistical tests

We compared CO_2 effluxes measured at differently prepared sites with those measured in the control forest using the *t*-test. We also studied the sources of variance within soil treatments and blocks (moisture and fertility gradient) by nested random effect analysis of variance. Systat 8.0 (SPSS Inc., Chicago, IL, USA) and SAS 6.12 statistical software (SAS Institute Inc., Cary, NC, USA) were used in the analysis.

Finally, we estimated annual CO_2 emissions from the soil over the three-year-long study period. To do so, hourly CO_2 efflux values were predicted and then integrated over the year. The hourly efflux was estimated by the following simple function.

$$r = \alpha e^{\beta T}, \tag{1}$$

where r is the soil CO_2 efflux (g m^{-2} h^{-1}), T is the soil temperature (°C), and α and β are fitted constants (Boone *et al.* 1998, Buchmann 2000). Parameters for the function were obtained by fitting the CO_2 effluxes measured biweekly from points where the logging residue was removed, from points where the logging residue was left on site after clear-cutting, and from the control forest to the average temperature in the O- and E-horizons at the respective measuring points. Parameters were fitted for each site preparation and year separately. Values for parameters α and β in Eq. 1 are presented in Table 2.

Results

Effects of clear-cutting and site preparation on soil temperature and moisture conditions

Clear-cutting increased daytime temperatures in the O- and E-horizons on average by 5 °C during the summer following the harvesting (Fig. 3b). The temperature conditions were usually not constant throughout the day, and especially on warm summer days, the variation in soil surface temperature could reach 10 °C. Soil temperatures were at their lowest between 7:00 and 8:00, reaching a maximum between 16:00 and 17:00. CO_2 effluxes were usually measured before noon (between 8:00 and 11:00), and the temperature increase in the humus layer during that time was 3–4 °C at most and in the E-horizon 2–3 °C. We tested the effect of the change in temperature on the results by standardizing the CO_2 effluxes measured on warm days to the morning temperature of the respective day. The temperature responses obtained from

Table 1. Number of places in which CO_2 efflux was measured during the experiment.

Year	Soil treatment					
	Control forest	Clear-cut with no logging residue	Clear-cut with logging residue	Exp. C-horizon	Exp. E-horizon	Mound
1997	–	3*	–	–	–	–
1998	4	3*	8	8	8	8
1999	4	3*	8	8	8	8
2000	4	3*	8	8	8	8

During 1997–1999 places on a clear-cut site with and without logging residue and in the control forest under the canopy were monitored once a week or every second week. Among the soil treatments, 2 out of 8 places were monitored equally, while the rest were monitored 2–3 times over the growing season. During 2000 all places were monitored 3 times.

*These places were established in June 1997 before clear-cutting in an undisturbed forest, and logging residue was removed from them after clear-cutting in 1998.

biweekly measurements were used in the standardization (Eq. 1). However, because the standardization had only a minor effect on the results, we will present only nonstandardized fluxes.

Forest harvest also affected soil water potential. In 1997, before the clear-cutting, the matric potentials were more variable and on average lower (less water in soil) than those in 1998, 1999, and 2000 (Fig. 3c). The highest matric potentials were measured in 1998. Precipitation varied considerably between the summers. The cumulative precipitation from 1 June to 30 September was 338, 410, 204, and 238 mm in 1997, 1998, 1999, and 2000, respectively.

Effects of clear-cutting and site preparation on instantaneous CO_2 effluxes

Prior to clear-cutting, mean CO_2 efflux from the undisturbed forest floor ranged from 0.05 g m^{-2} h^{-1} in November to 0.93 g m^{-2} h^{-1} in July (Fig. 3a). The CO_2 efflux followed the same pattern as the average temperature in the O- and E-horizons, which reached a maximum temperature of about 20 °C in summer (Fig. 3b). Based on ten measurements at three points, the average CO_2 efflux rate from 25 June to 24 September was 0.49 g m^{-2} h^{-1}.

After clear-cutting in 1998, the highest CO_2 effluxes measured from places where the logging residue was left on site and from the mounds, were 0.83 and 0.97 g m^{-2} h^{-1}, respectively (Table 3). These places showed effluxes twice as high as those of the adjacent control forest or sites from which the logging residue was removed. If a mound of a mixture of logging residue, humus, and mineral soil was piled on top of the soil, the efflux rate was equal or slightly higher than when logging residue was left on soil. Annual average efflux rates from mounds and from sites with logging residue are presented in Table 4. The mixing of organic material with mineral soil initially seemed to increase CO_2 efflux, but this effect leveled off rapidly. In 1999 and 2000, the CO_2 effluxes from the mounds and from the clear-cut sites without site preparation or removal of logging residue had dropped to the same level or lower than those measured in the control forest.

When the logging residue was removed from the top of the soil, only root litter and possibly a small amount of deteriorated forest floor vegetation remained decomposing in the soil. After clear-cutting in 1998, the average CO_2 efflux rate with this treatment was 0.35 g m^{-2} h^{-1}, which is 0.2 g m^{-2} h^{-1} lower than in the control forest (Table 4). When the O- or E-horizon was removed, the average rate measured from the mineral soil between June and September varied from 0.10 to 0.23 g m^{-2} h^{-1}. The efflux was somewhat higher, when the E-horizon was left intact, and seemed to increase with time from the clear-cut.

We detected no systematic differences in CO_2 effluxes along the moisture and fertility gradients of our study site, neither before nor after the clear-cutting. Most of the variation in soil CO_2 efflux originated from site preparation, which accounted for over 75% of the total variance. The spatial variation increased over the summer together with respiration, peaking during the highest effluxes in July and August. In the forest soil before harvest, CO_2 efflux was higher and spatially more variable than that measured from the same sites after clear-cutting

Table 2. Parameters α and β used in temperature response functions (Eq. 1) for predicting annual effluxes.

Year	Control forest		Clear-cut site with logging residue		Clear-cut site with no logging residue	
	α	β	α	β	α	β
1997					0.1089	0.1086
1998	0.1146	0.1196	0.1645	0.1064	0.1237	0.0754
1999	0.1197	0.107	0.2047	0.0637	0.0927	0.105
2000*	0.1197	0.107	0.2047	0.0637	0.0927	0.105

*Annual effluxes for 2000 were calculated using temperature responses measured in 1999.

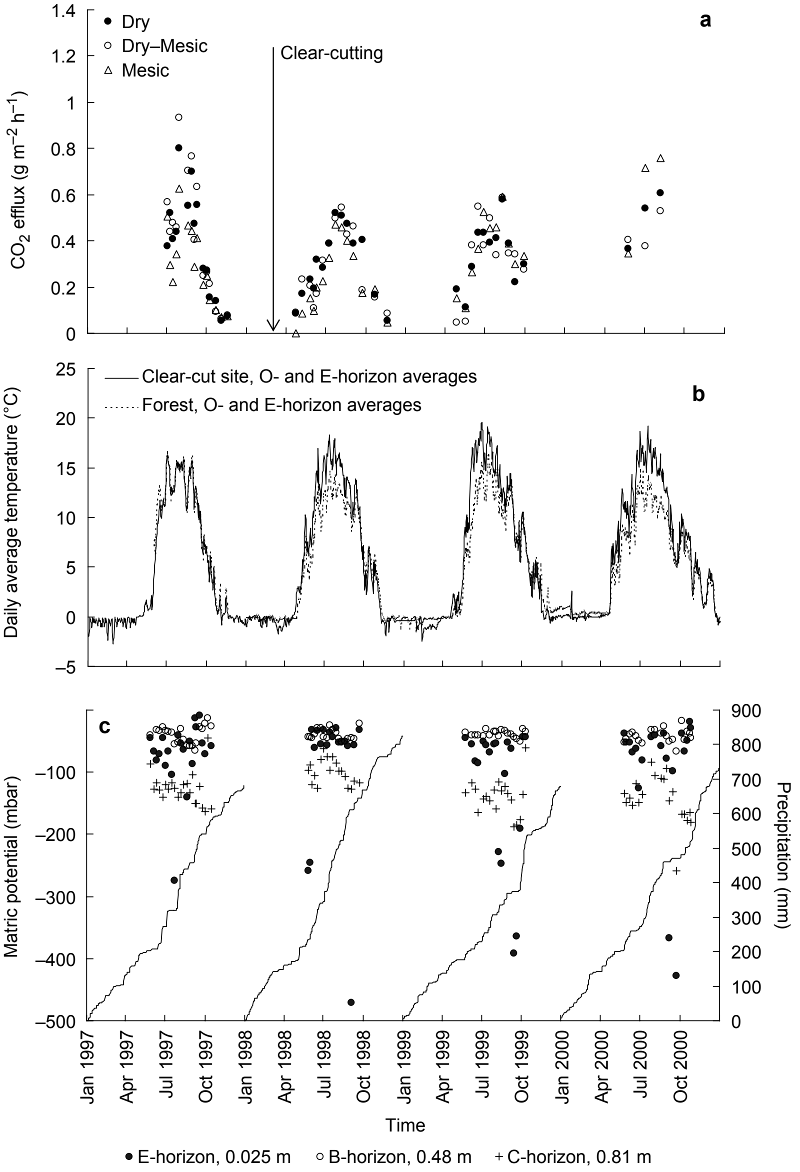

Fig. 3. — **a**: CO_2 efflux measured either weekly or bimonthly from the three collars in June 1997 to August 1999 and three times in 2000. — **b**: Daily average soil temperatures at the clear-cut site and in the control forest with soil temperatures presented as an average of O- and E-horizons. — **c**: Soil matric potential in E-, B-, and C-horizons and cumulative annual precipitation. The forest was clear-cut in March 1998.

(Fig. 3a). On the clear-cut sites where no soil preparation was applied, the spatial variation was smallest.

Estimation of annual CO_2-C losses from soil after clear-cutting and soil preparation

Estimated annual CO_2 emission before the clear-cutting was 1900 g m^{-2} in 1997. Most of the CO_2 emitted (1602 g m^{-2}) was produced between April and November that year. After clear-cutting and removal of logging residue, annual CO_2 emissions remained virtually unchanged, at 1819, 1960, and 1985 g m^{-2} in 1998, 1999, and 2000, respectively (Fig. 4a). In the adjacent control forest, the corresponding annual CO_2 emissions were 2096, 2130, and 2054 g m^{-2}.

Estimated annual CO_2 emissions were much higher from places where the logging residue was left on site after clear-cutting: 3242, 2845, and 2926 g m^{-2} during the three years following the harvest. The total amount of carbon released on the clear-cut site in tree residues was about 4700 g m^{-2} of which about 36% was in tree crowns, 26% in stumps and 38% in roots. The amount of carbon in the above-ground logging residue was about 1692 g m^{-2}. Assuming that the logging residue is evenly distributed over the entire clear-cut site, we can estimate CO_2 emission originating from the logging residue by subtracting the emissions from places without logging residue from those with logging residue. During the first year after clear-cutting the CO_2 emissions were 1423 g m^{-2}, equaling 388 g m^{-2} of

Table 3. Soil CO_2 efflux measured from the control forest and from the clear-cut site with different site preparations. The CO_2 efflux (g m^{-2} h^{-1}) of each soil treatment was compared with that of the control forest with the *t*-test, and *p* values and standard errors (SE) are indicated.

Day	Control forest		Mound		Clear-cut with logging residue		Exposed C-horizon		Exposed E-horizon		Clear-cut no logging residue	
	Efflux	SE	Efflux	SE	Efflux	SE	Efflux	SE	Efflux	SE	Efflux	SE
24 Jun. 1998	0.47	0.036	0.97*	0.192	0.83*	0.078	0.06*	0.025	0.17*	0.037	0.28*	0.025
09 Jul. 1998	0.48	0.041	0.81–	0.318	0.34–	0.199	0.15–	0.127	0.16–	0.057	0.37†	0.021
22 Jul. 1998	0.54	0.039	1.18–	0.514	0.89–	0.047	0.14–	0.046	0.19–	0.090	0.50°	0.014
05 Aug. 1998	0.56	0.072	0.96–	0.431	0.95–	0.110	0.13–	0.044	0.15–	0.082	0.50°	0.025
19 Aug. 1998	0.64	0.117	0.76°	0.124	0.74°	0.061	0.13*	0.035	0.16*	0.042	0.43°	0.021
03 Sep. 1998	0.45	0.044	0.50–	0.325	0.47–	0.126	0.18–	0.023	0.09–	0.037	0.40°	0.045
25 Sep. 1998	0.25	0.031	0.30–	0.180	0.19–	0.001	0.06–	0.036	0.09–	0.059	0.26°	0.074
22 Oct. 1998	0.17	0.011	0.16–	0.095	0.18–	0.004	0.10–	0.036	0.02–	0.015	0.17°	0.010
02 Jun. 1999	0.33	0.026	0.59*	0.101	0.39°	0.090	0.15*	0.046	0.21*	0.045	0.31°	0.036
16 Jun. 1999	0.33	0.026	0.93–	0.322	1.24–	0.064	0.18–	0.022	0.22–	0.115	0.45°	0.053
28 Jun. 1999	0.44	0.023	0.83*	0.151	0.28*	0.028	0.15*	0.027	0.18*	0.023	0.45°	0.042
14 Jul. 1999	0.45	0.057	0.75–	0.236	0.46–	0.086	0.19–	0.002	0.29–	0.005	0.45°	0.031
28 Jul. 1999	0.52	0.036	0.79–	0.308	0.62–	0.064	0.14–	0.032	0.24–	0.145	0.40†	0.035
10 Aug. 1999	0.67	0.094	0.18–	0.030	0.70–	0.049	0.08–	0.018	0.21–	0.076	0.59°	0.003
25 Aug. 1999	0.54	0.088	0.37°	0.057	0.33†	0.026	0.09*	0.004	0.10*	0.020	0.38°	0.015
24 May 2000	0.35	0.020	0.41°	0.056	0.41°	0.065	0.16*	0.024	0.18*	0.032	0.37°	0.017
04 Jul. 2000	0.54	0.087	0.46°	0.056	0.44°	0.074	0.17*	0.027	0.24*	0.029	0.55°	0.098
08 Aug. 2000	0.58	0.041	0.58°	0.119	0.64°	0.097	0.19*	0.029	0.28*	0.058	0.63°	0.068

$^*p < 0.05$, $^{\dagger}0.05 < p < 0.1$, and $^{\circ}p > 0.1$.

– No *t*-test was performed because measurements were done on only two blocks.

Table 4. Average soil CO_2 effluxes (g m^{-2} h^{-1}) and standard errors (SE) measured from all blocks twice in 1998 and three times in 1999 and 2000.

Day	Control forest		Mound		Clear-cut with logging residue		Exposed C-horizon		Exposed E-horizon		Clear-cut no logging residue	
	Efflux	SE	Efflux	SE	Efflux	SE	Efflux	SE	Efflux	SE	Efflux	SE
1998 average	0.55	0.07	0.86	0.11	0.78	0.05	0.10	0.02	0.17	0.03	0.35	0.04
1999 average	0.44	0.04	0.59	0.07	0.33	0.03	0.13	0.02	0.16	0.02	0.38	0.03
2000 average	0.49	0.04	0.49	0.05	0.51	0.05	0.17	0.01	0.23	0.02	0.52	0.05
Average	0.49	0.05	0.65	0.08	0.54	0.04	0.13	0.02	0.19	0.02	0.42	0.04

Minimum proportion of root respiration in 1998 = (Control forest – Clear-cut with no residue)/Control forest = 0.36.
Maximum proportion of root respiration in 1998 = (Control forest – Exposed E-horizon)/Control forest = 0.69.
Decomposition of below-ground litter at the clear-cut in 1998 = (Clear-cut with no residue – Exposed C-horizon) = 0.25 g CO_2 m^{-2} h^{-1}.

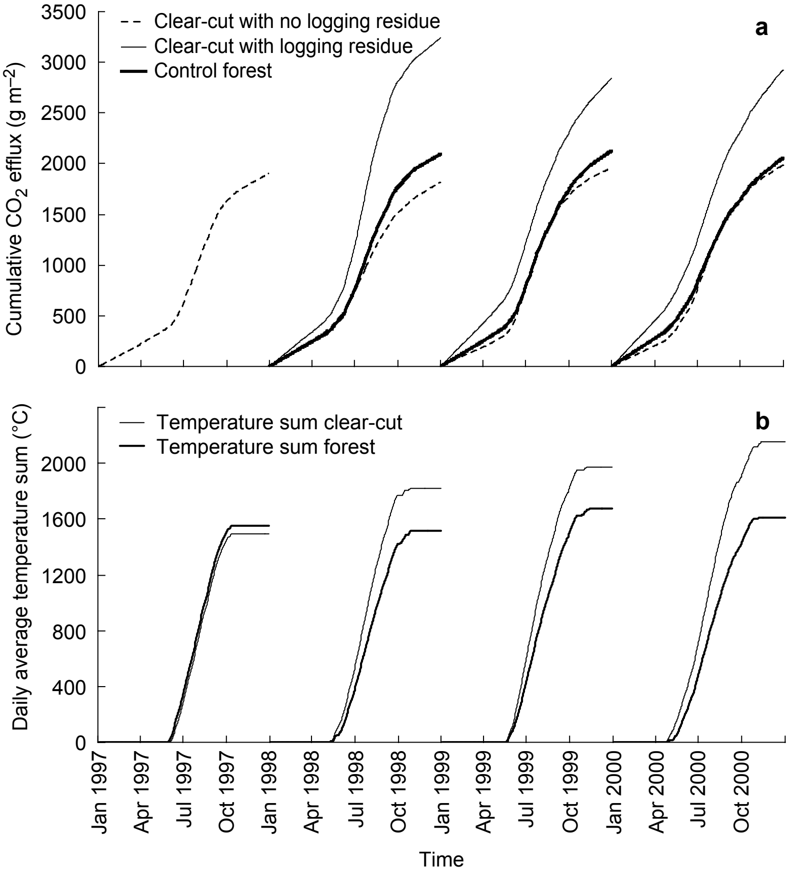

Fig. 4. — **a**: Estimated annual soil CO_2 effluxes. — **b**: Daily soil temperature sum with 5 °C threshold value measured from the respective sampling points during 1997–2000.

C and consequently, the amount of carbon emitted to the atmosphere during the first year after clear-cutting was some 23% of the total added on top of the soil upon clear-cutting.

The amount of carbon in roots was 1786 and in stumps 1222 g m^{-2}. Most of the roots were located in O-, E-, and B-horizons. We can estimate the mass loss from this root litter pool by subtracting the annual emissions from C-horizon from that from the top of the soil on measuring points from which logging residue was removed, i.e. we assume that the CO_2 emissions originate mostly from the decomposition of roots. The annual CO_2 emissions from places without logging residue were 1819 g m^{-2} equaling to 496 g m^{-2} of C. The average annual CO_2 emissions from C-horizon were about 29% of that from the places without logging residue (Table 4); as a result, the annual carbon emissions from C-horizon were about 144 g m^{-2}. Thus, the annual C emissions from the O-, E- and B-horizons during the first year after clear-cutting were about 352 g m^{-2}, which was about 20% of the root mass.

Between 1997 and 2000, the temperature response function explained on average 71% of the measured efflux in places where the logging residue was removed after clear-cutting (Fig. 5a). In places where the logging residue was left on site and in the control forest, the temperature response function underestimated high effluxes (Fig. 5b and c). The R^2 for sites with logging residue and for the control forest was 0.51 and 0.44, respectively.

Discussion

Effect of clear-cutting on CO_2 efflux

The CO_2 effluxes measured from boreal forest soils have ranged from 0 to 3.60 g m^{-2} h^{-1} (Morén

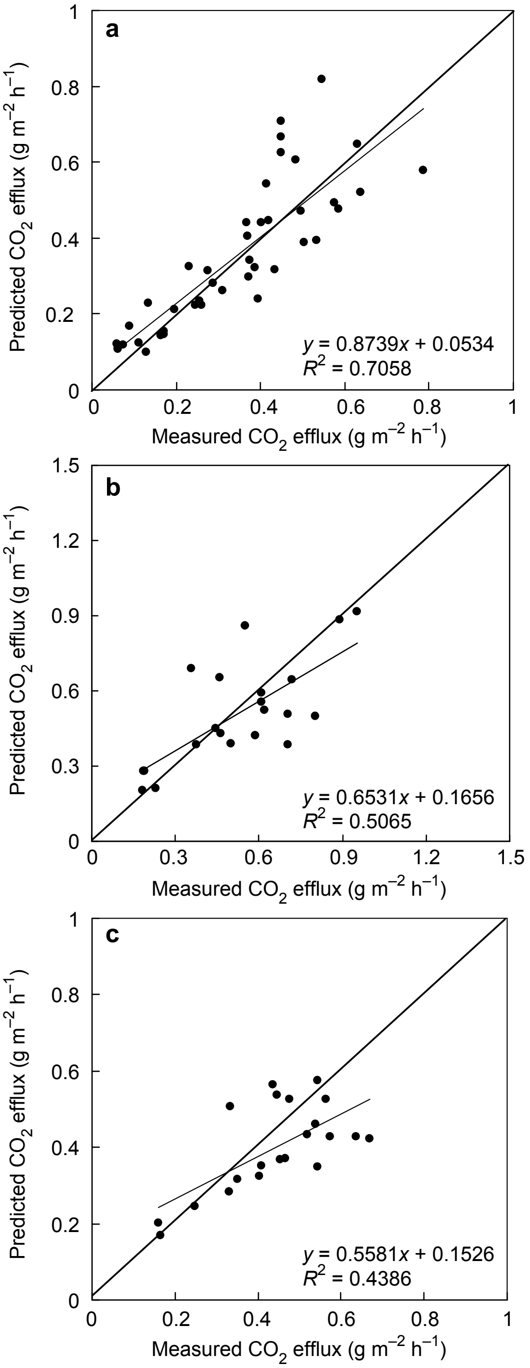

Fig. 5. Measured and predicted soil CO_2 effluxes (**a**) in 1997–2000 from the three sampling points where the logging residue was removed after clear-cutting, (**b**) in 1998–2000 from points where the logging residue was left on site, and (**c**) from the control forest. Predicted values are based on the temperature response of soil CO_2 efflux and the average temperature of O- and E-horizons.

and Lindroth 2000, Widén and Majdi 2001, Pumpanen *et al.* 2003). The highest effluxes in the northern hemisphere, typically measured in July and August, have attained a maximum of 1 g m^{-2} h^{-1}, with the lowest effluxes in winter ranging between 0.001 and 0.1 g m^{-2} h^{-1}. We found effluxes in the lower end of the reported range (0.00–0.97 g m^{-2} h^{-1}), and that the efflux pattern was related to soil temperature.

Spatial variation in the CO_2 efflux from the undisturbed forest floor was high, especially during the summer periods with high effluxes. This was probably due to variation in root and rhizosphere respiration. While, according to Hanson *et al.* (2000), root and rhizosphere respiration may contribute 10%–90% of total soil respiration, most estimates range from 33% to 62% (Ewel *et al.* 1987b, Bowden *et al.* 1993, Epron *et al.* 1999, Högberg *et al.* 2001, Widén and Majdi 2001). In our study, the average CO_2 efflux from the clear-cut site after removal of logging residue was 0.2 g m^{-2} h^{-1} lower than in the control forest, suggesting that the proportion of rhizosphere respiration would be at least 36%. (Table 4).

An estimate of maximal soil respiration in the humus layer can be obtained by comparing CO_2 effluxes measured from the E-horizon with those from the control forest. When the efflux from the E-horizon, 0.17 g m^{-2} h^{-1} in 1998, is subtracted from the efflux of 0.55 g m^{-2} h^{-1} from the control forest, it can be assumed that on average 0.38 g m^{-2} h^{-1}, or 69%, comes from humus layer respiration. Furthermore, when subtracting the C-horizon CO_2 efflux from the treatment without logging residue, we can estimate that the CO_2 efflux from the decomposition of belowground litter at the clear-cut site would be about 0.25 g CO_2 m^{-2} h^{-1} (Table 4).

As compared with that from the forest, the measured CO_2 efflux was higher from the sampling points where the logging residue was left on site and lower from the points where the logging residue was removed. Evidently, the CO_2 release from the decomposition of fresh root litter was insufficient to compensate for the CO_2 released from root and rhizosphere respiration. The higher CO_2 efflux from the measuring points where the logging residue was left was apparently due to the rapid decomposition of fresh above-ground litter.

The sampling points on the clear-cut site and in the control forest differed from each other in terms of ground vegetation (Levula *et al.* 2003). Control plots included live forest floor vegetation, mainly mosses, which differed both from vegetation on the clear-cut site and from sampling points where the logging residue was left on site. The contribution of the respiration of ground vegetation may have had affected the comparison of different treatments. Silvola (1986) measured dark respiration for forest mosses (*Dicranum majus* Turn. and *Pleurozium schreberi*) as ranging between 0.05 and 0.1 g CO_2 m^{-2} h^{-1} at 10 °C and at water content optimal for photosynthesis. Had mosses been removed from our chambers, the total soil CO_2 efflux might have been about 10%–20% lower. This would have increased our estimation of the contribution of root and rhizosphere respiration and decreased the estimation of humus layer respiration. The contribution of surface vegetation respiration would nevertheless be small relative to the effects of different site preparations.

Effect of site preparation on CO_2 efflux

The mounds showed slightly higher CO_2 efflux than the points where logging residue alone was left on site, probably because in the mounds organic matter and mineral soil were partially mixed, providing favorable temperature and moisture conditions for decomposing organisms. With soil preparation, soil structure is modified so that aeration is increased, and consequently, the decomposition of organic matter is enhanced. In addition, the increase in soil temperature brought about by soil preparation may facilitate decomposition (Edwards 1975, Salonius 1983, Palmer Winkler 1996, Davidson *et al.* 1998).

Most of the fresh easily decomposable organic matter in the mounds seemed to decay during the first summer after clear-cutting. In summer 1999 the elevated CO_2 efflux had already declined, and effluxes from mounds and from clear-cut sites with logging residue were almost equal to those from sites in which logging residue had been removed. The declining decomposition rate agrees with that presented by Berg *et al.* (1984) and Prescott *et al.* (2000b), who also found the highest decomposition rates during the first year. In their study, about 28%–30% of the mass of coniferous litter was lost in the first year, but the decomposition slowed so that after three years approximately 40%–50% of the original litter mass still remained on site.

The lowest CO_2 effluxes were measured at sampling points where the O- and E-horizons were removed, which is obvious, since most of the potentially decomposable soil organic matter was simultaneously removed. Situated in the lower B- and C-horizons was primarily bare mineral soil containing little organic matter. Pietikäinen *et al.* (1999) found the highest respiration rates in the uppermost 0.1 m of the soil, which contributed 91%–92% of the basal soil respiration on the same site as in this study before harvesting.

The increase in soil CO_2 efflux from exposed E- and C-horizons during the third summer after the clear-cutting could be explained by plants recolonizing on the exposed soil. A considerable number of *Poa pratensis* L. and *Deschampsia flexuosa* L. were observed at all sampling points in the second and especially in the third summer following the harvesting.

Effect of clear-cutting and site preparation on annual CO_2-C losses from soil and soil C stocks

Lytle and Cronan (1998) reported a cumulative soil CO_2 efflux of 1393 g m^{-2} over a period from May to November in a spruce forest in Maine, USA. Morén and Lindroth (2000) observed a much higher annual forest floor respiration, 4500 g m^{-2}, in a mixed Norway spruce Scots pine forest in southern Sweden. In our study, the annual soil CO_2 effluxes were consistent with previous studies.

Unlike the instantaneous CO_2 effluxes, the annual CO_2 effluxes decreased only slightly after the clear-cutting and removal of logging residue even though most of the root and rhizosphere respiration was eliminated when the trees were removed. The loss of root and rhizosphere respiration may have been compensated for by higher temperature at the clear-cut site, enhancing the decomposition of below-ground organic matter. Because the estimation of annual CO_2 effluxes was based on temperature response, the diurnal temperature cycle affected the prediction of annual fluxes. When the tree canopy was removed, the daytime high temperatures in the soil surface increased, resulting in relatively high annual effluxes.

Substantial CO_2 amounts were emitted into the atmosphere from the logging residue during the first year following the harvesting. These emissions were 23% of the amount of C released on the clear-cut site as above ground logging residue, and 20% of that in the roots. At these annual mass loss rates, 73% of the logging residue and 67% of the decaying roots would become decomposed in 5 years. After 15 years the overall mass losses would be 98% and 96%, respectively. If stumps were pooled with roots, 46% would become decomposed in 5 years and 85% in 15 years. However, according to Berg *et al*. (1984) and Prescott *et al*. (2000a, 2000b), the decomposition rate of litter is not linear, instead slowing down over time. Moreover, the CO_2 effluxes measured from the logging residue in this study originated mostly from the decomposition of material fine enough to fit inside the chamber used for flux measurements, such as needles and small branches. A large part of the carbon in the logging residue is in coarse woody debris, such as thick branches as well as in roots, and stumps, the decomposition of which takes considerably longer than that of fine litter. For example, according to model calculations based on the literature review by Liski *et al*. (1998), the decomposition rate of fine woody litter such as Scots pine needles is about 3.5 times higher than that of branches and 16 times higher than that of boles during the first 5 years of decomposition. Therefore, in the long run the actual mass losses of the logging residue and the roots are probably much lower than those presented here.

Recent studies on the carbon balance of young forest stands have shown that boreal coniferous forests change from a carbon source to a sink no earlier than at an age of about 15 years (Karjalainen 1996a, 1996b, Schulze *et al*. 1999, Liski *et al*. 2001). Based on three years of monitoring after clear-cutting, we cannot estimate the decomposition rate and changes in the soil carbon stocks accurately in the long run. However, already with this data, we know that the decomposition of coarse logging residue is likely to take longer than 15 years, i.e. longer than the time required for the new forest stand to start acting as a carbon sink again. Extending the calculation over subsequent forest crop rotations, boreal forests would continuously act as carbon sinks as accumulation in soil exceeds SOM decomposition. However, to draw firm conclusions on the effect of clear-cutting on soil carbon stocks, long-term monitoring of the carbon dynamics of the clear-cut site, the newly established forest and ground vegetation is needed.

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