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Saana Kataja-aho

Short-Term Responses of Decomposers and Vegetation to Stump Removal

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ABSTRACT

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Stump removal has become a common practice to produce raw material for bioenergy production. It was hypothesized that stump removal is an extensive and more intense disturbance for forest ecosystems (soil decomposer organisms and vegetation) compared to traditional site preparation after clear cutting. Therefore, the effects of stump harvesting on forest soil decomposers, vegetation and nutrient dynamics in undisturbed patches of the forest soil and in exposed mineral soil were compared to the effects of the traditional site preparation method, mounding. Nematodes and enchytraeids were the only decomposer groups that were directly affected (negatively) by the stump removal. Regardless of the treatment, the abundances of most of the decomposer groups were consistently lower in the exposed mineral soil than in the intact forest soil. There was 2-3 times more exposed mineral soil in stump removal sites compared to mounding sites. When this was taken into account, the decomposer community was negatively affected by the stump removal at the forest stand level. However, the greater soil disturbance at the stump harvesting sites enhanced CO_2 production, net nitrogen mineralisation and nitrification. The increased N availability and the changes in microclimate due to the disturbance probably explained the vegetation increase at the stump harvested sites. Planted Norway spruce seedlings grew faster during the first two growing periods at the stump removal sites than at the mounding sites. The seedlings had high and similar ectomycorrhizal colonization rate in both treatments. In the short-term, it is probably not the resources removed in the stumps themselves, but the degree and amount of soil disturbance during the stump harvesting procedure that affects the decomposer community and its function in the clear-felled stands.

Keywords: Bioenergy; boreal forest soil; decomposer community; forest management; Norway spruce; nutrient dynamics; stump harvesting.

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

The thesis is based on the following original papers, which will be referred to in the text by their Roman numerals I-IV.

I Kataja-aho, S., Saari, E., Fritze, H., Haimi, J. 2011. Effects of stump removal on soil decomposer communities in undisturbed patches of the forest floor. Scandinavian Journal of Forest Research 26: 221-231.

II Kataja-aho, S., Fritze, H., Haimi, J. 2011. Short-term responses of soil decomposer and plant communities to stump harvesting in boreal forests. Forest Ecology and Management 262: 379-388.

III Kataja-aho, S., Pennanen, T., Lensu, A., Haimi, J. 2011. Does stump removal affect growth and mycorrhizal infection of spruce (*Picea abies*) seedlings in clear-cuts? Manuscript.

IV Kataja-aho, S., Smolander, A., Fritze, H., Norrgård, S., Haimi, J. 2011. Responses of soil carbon and nitrogen transformations to stump removal. Submitted manuscript.

The table shows the contributions to the original papers.

	I	II	III	IV
Original idea	JH, ES, HF	SK, JH, HF	SK, TP	SK, JH, AS
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SK = Saana Kataja-aho, JH = Jari Haimi, HF = Hannu Fritze, TP = Taina Pennanen, AS = Aino Smolander, AL = Anssi Lensu, ES = Eeva Saari, SN = Sini Norrgård

1 INTRODUCTION

1.1 Forest management, disturbance and climate change

Forest ecosystems are highly variable in structure and function. The heterogeneity of habitats and species living in them are called biodiversity (Kouki 1994). Biodiversity is dependent on the disturbances which generally determine the characteristics of the habitat mosaic, which in turn affect the population dynamics of the certain habitat (Kuuluvainen 2002). Preservation of diversity in forestry has become a major issue during the last few decades because losses of diversity may harm the life-supporting ecosystem processes, such as primary productivity, water retention, production of oxygen, pollination, carbon storage, decomposition, nutrient cycling, and supplying clean water (Bengtsson *et al.* 2000). Diversity may also affect ecological stability and, therefore, preserving diversity may be essential for long-term sustainability (Bengtsson *et al.* 2000).

Forest management, including fellings and all site preparation methods, is replacing natural disturbances that are caused by fires, storms, insects and pathogens for example (Esseen *et al.* 1997). Forest management has a long history in Finland. Nowadays, commercial forests are not only harvested for timber and pulp and paper production, but more and more for energy production. Fuel wood is collected as thinnings of young forest stands, in addition to felling residues and stump removals after clear felling (Ylitalo 2010). Forest-derived fuels, used as woodchips, consist mainly of logging residues such as branches and small trees from thinnings and management of young stands. At present, stumps and main roots from regeneration felling areas are also used to increase the forest fuel production (Halonen 2004, Laitila *et al.* 2008).

Boreal forests, which cover approximately 15% of the Earth's continental surface area, play a major role (together with tropical forests and oceans) in Earth's carbon sequestration. The important boreal forest ecosystem, especially the trees, stores up the carbon (C) of carbon dioxide (CO_2) from the atmosphere through photosynthesis into biomass, mitigating at the same time the phenomenon called global warming. On the other hand, forests also return large amounts of C to the atmosphere through respiration by plants and decomposers in the soil.

In light of global warming and emissions trading, interest in using renewable fuels has increased. Forest biomass has been seen as one solution to produce renewable fuels. In the beginning of stump harvesting in Finland, approximately ten years ago, the stumps along with other forest biofuels were considered to be a carbon neutral fuel source since they, as trees in general, bind the carbon during their growth, which is later released in cuttings/burnings. However, according to Repo *et al.*, (2010) the total emissions caused by the production of forest bioenergy (stumps included) are comparable to the emissions of fossil fuels during a couple of decades from the start of the bioenergy production. Later, however, the indirect emissions decrease.

Forest ecosystems contain a large part of the carbon accumulated on land, both in the form of biomass and soil organic matter. In addition, forest soils act as long-term carbon sinks by binding the carbon and other nutrients (mainly nitrogen and sulfur). The formation of boreal forest soils has taken hundreds (or even thousands) of years after the last glaciation. Alterations in the carbon and nitrogen cycles by mixing the soil layers during forest management, for example, may be costly over the long run, as resources are lost from the system. Increased fluxes of carbon to the atmosphere, as occurs when wetlands are drained, land is converted to agriculture or forest soils are massively prepared for replanting, contribute to the additions of main greenhouse gases (specifically CO_2 and methane (CH_4)), which may influence the global warming phenomenon (Daily *et al*. 1997). In addition to the reduction of carbon fluxes to the atmosphere, the storage of carbon in the soil, the soil organic matter and the interactions with soil organisms have profound roles in the regulation of soil fertility, the maintenance of soil structure and the decomposition of dead organic matter (Hopkins and Gregorich 2005), although soil organisms regard organic compounds simply as substrates supplying resources and energy. Tree harvesting and regeneration practices have direct extensive effects on forest ecosystems through changes in plant cover, microclimate, distribution of organic matter, nutrient mineralisation and soil compaction, for example (Marshall 2000), and stump removal may further heighten these effects.

1.2 Stump removal as a management practise

Stumps are removed mainly from Norway spruce (*Picea abies* (L.) Karst.) dominated clear felled stands (Halonen 2004), as well as from the clear-cuts stricken by root rot (e.g. *Heterobasidion* sp.) to avoid infection of the next tree generation (Thies and Westlind 2005; Müller *et al.* 2007; Zabowski *et al.* 2008). In Finland, 400 – 600 stumps per hectare are removed from stump harvesting sites (Äijälä *et al.* 2010). The diameter of the removed stumps should be more than 15 cm, anything smaller and all decaying stumps are left untouched (Äijälä *et al.* 2010). In addition, forestry guidelines suggest leaving at least 25 large stumps (diameter >15 cm) of different tree species per hectare untouched (Äijälä *et al.* 2010).

The harvesting of stumps, in addition to other forest management practices, can alter the forest floor by replacing the vegetation and most of the soil's organic layers, thereby exposing mineral soil in large areas. For instance, three to four times more mineral soil surface is exposed during stump harvesting compared to traditional site preparation practices, such as mounding and harrowing, and a large amount of organic matter is mixed with mineral soil (Strandström 2006, Rabinowitsch-Jokinen and Vanha-Majamaa 2010). In addition, the amounts of nutrients removed in stumps and logging residues may almost be as high as what is lost in removed stems (Palviainen 2005). Regardless of the exposure of mineral soil in stump removal sites, each site must still be prepared through mounding practices, to ensure sufficient planting sites for tree seedlings (Äijälä *et al.* 2010).

As stump removal is a rather novel method, the effects on the structure and functioning of the diverse soil decomposer community are still unexplored. The more extensive use of renewable energy sources may significantly increase their environmental impacts on forest biota due to more intense management practices and greater disturbance of the soil.

1.3 Responses of forest soil organisms and decomposition processes to forest management

1.3.1 Soil decomposers

The decomposer community consists of different kinds of organisms, including microflora, protista, nematoda, enchytraeids, micro- and macroarthropods and earthworms, which all derive their energy and nutrition from dead organic matter. Doing so, they decompose the matter and finally mineralize nutrients (Bardgett 2005). Microflora, i.e. bacteria and fungi, forms the most important organism group because they recycle nutrients from dead organic matter into inorganic forms, which plants can reuse (Coleman *et al.* 2004, Bardgett 2005). Nematodes (Nematoda) are the most numerous animals in soil and their role in decomposition processes is either direct via excretion of nutrients into soil or indirect through altering the size, composition and activity of the microbial community (Ingham *et al.* 1985, Huhta *et al.* 1986, Bardgett 2005). Enchytraeid worms (Enchytraeidae, Oligochaeta) are considered keystone species in boreal forest soils, where they can constitute some 75% of the total faunal biomass (Didden 1993). Enchytraeids ingest both mineral and organic particles in the soil, significantly affecting organic matter dynamics and the physical structure of soil, as do earthworms though they are rather sparse in boreal forest soils.

The diet of enchytraeids includes plant material enriched with fungal hyphae and bacteria (Coleman *et al.* 2004, Didden 1993). Microarthropods, such as mites (Acari) and springtails (Collembola), are very diverse in soils and have a significant impact on the decomposition process and net N mineralisation in the forest floor (Persson 1989, Coleman *et al.* 2004). Among mites, there are microbivores, detritivores, predators and fungivores, while most collembolans are considered as fungivores (Coleman *et al.* 2004). Macroarthropods include spiders (Araneida), ants (Formicidae), beetles (Coleoptera), millipedes (Myriapoda) and many larvae of beetles, moths (Noctuidae, Lepidoptera) and Diptera, which live on the soil surface or just beneath it their whole life or for parts of their lifecycle. Macroarthropods may have direct effects on soil structure due to links between aboveground and belowground food webs. Macroarthropods may also modify the belowground food webs by feeding on microarthropods (Coleman *et al.* 2004).

The habitat sizes and diversity patterns differ significantly between above- and belowground communities. Habitat scale of decomposers is usually smaller than that of aboveground fauna. The structure of the soil, i.e. the spatial arrangement of solids, liquids, solutes, pores and gases, determines the physical framework in which the soil biota lives and functions, and shows extensive heterogeneity across a very wide range of size scales (Ritz 2005). The compact and heterogeneous nature of the soil matrix is the main factor constraining soil biodiversity providing nonpareil potential for niche partitioning, thus allowing for high levels of local diversity. At the local scale, above and below ground subsystems are linked mainly via plants, and thus the diversity of belowground biota appears to be very context dependent (De Deyn and Van der Putten 2005).

Human-caused habitat loss and fragmentation are the main threats for many organisms. According to the metapopulation theory (Hanski 1999), habitat fragments that remain undisturbed or are only slightly changed may later act as sources for colonization of damaged patches, thus preventing population extinctions at the landscape level. In boreal forests, various forest management practices, such as thinning, partial or clear cutting, and harrowing, trenching, ditching and mounding for regeneration purposes, change the forest floor by removing the vegetation and organic soil layers, thereby exposing the mineral soil. Large amounts of organic matter are also mixed with mineral soil. As a consequence, the habitat of soil organisms changes; the continuous forest floor fragments into patches of different habitat quality. Stump removal is an even more invasive procedure than above mentioned methods, since the soil of stump removal sites are prepared more thoroughly and deeper than sites retaining stumps. Consequently, various forest regeneration methods have been shown to have some effects, mainly negative, on soil decomposer communities, although in general, soil organisms seem to be rather resistant to habitat fragmentation (Rantalainen *et al.* 2008) and well buffered against other habitat changes resulting from forestry, such as changes in micro-climate and root exudation (Siira-Pietikäinen *et al.* 2001). However, organic matter removal can affect soil food web for at least a few decades (Bengtsson *et al.* 1998). Furthermore, recently exposed mineral soil is a hostile environment for most soil fauna (see e.g. Siira-Pietikäinen *et al.* 2003a). Stump removal increases the extent of exposed mineral soil (Rabinowitsch-Jokinen and Vanha-Majamaa 2010) and, thus, in the stump removal areas there is less high quality habitat for decomposers than in traditionally prepared (i.e. mounded or harrowed) areas.

1.3.2 Nutrient dynamics in soils

The decomposition process breaks up detritus into carbon dioxide (CO_2) and soil organic matter, and releases nutrient elements into the soil, which eventually are accumulated by plants. Terrestrial plant growth is highly dependent on the decomposition system and heterotrophic organisms in the soil are ultimately responsible for ensuring the availability of nutrients for primary production (Wardle 2002). During the decomposition process, elements, such as carbon (C), nitrogen (N), calcium (Ca), magnesium (Mg), potassium (K), sulphur (S), phosphorus (P) and sodium (Na), are converted from organic to inorganic forms (mineralized). For example, as plant litter decomposes the elemental mix changes as a result of differential mobility and biological fixation (Coleman *et al.* 2004). In natural ecosystems, most N and a portion of the P required for plant growth are supplied through decomposition of organic matter. The N and P are the two nutrients that most limit primary productivity in natural and managed terrestrial ecosystems (Bardgett 2005, Chapin *et al.* 2002).

Forest harvesting itself affects nutrient cycling in various ways, for instance the soil water content and temperature increases due to opened canopy and eliminated uptake by trees (Keenan and Kimmins 1993). This may enhance the decomposition process and increase the nutrient availability and, futhermore, the risk of nutrient leaching (Keenan and Kimmins 1993). In whole tree harvesting (WTH, all above-stump biomass removed), the increased biomass removal may result in a significant increase in nutrient losses, leading to potential negative effects on future site productivity and, consequently, on stand growth (e.g Mälkönen 1976, Palviainen *et al.* 2004, Palviainen 2005, Egnell 2011). Egnell (2011) showed that after WTH, the reduction in tree growth was temporary. The reductions in growth were larger in WTH compared to other harvesting intensities, such as stem-wood only, branch and stem harvest only with needles left on site (Egnell 2011). Although the nutrient content of stumps is quite low (Palviainen 2005), the turnover of soil layers that occurs during stump removal may have more of an effect on the forest ecosystem than WTH. The physical disturbance of soil in stump removal procedure produces changes in properties like in soil temperature and moisture content, which may result in clear changes in soil nutrient transformations and declines in soil nitrogen, as well as other nutrients (Staaf and Olsson 1994, Hope 2007, Zabowski *et al.* 2008). The process is evidently causing elevated rates of decomposition of dead organic matter in the surface soil layers (Hope 2007).

Clear transient changes have been observed in N mobilization after stump harvesting in Norway spruce forest in SW Sweden (Staaf and Olsson 1994). Additionally, stump removal has lead to rather long-term decline in mineral N in Douglas-fir (*Pseudostuga menziesii*) stands (Zabowski *et al.* 2008). Furthermore, significant decreases in surface soil reserves of carbon and nutrients after stump removal followed by scarification was found after both one and ten years in forests dominated by western red cedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*) (Hope 2007). However, carbon and nutrient reserves in the mineral horizon were increased in the stump removal plots (Hope 2007). Thus, when stump removal after clear felling is applied systematically on a larger scale in forestry, it is evident that there will be changes in soil C and nutrient cycling.

It has been proposed that changes in soil nutrient stocks are due to the elevated rates of decomposition of soil organic matter after physical disturbance, rather than direct removal of C and nutrients in stumps and roots (Hope 2007, Walmsley and Godbold 2010). Stump removal may affect soil processes and resources of decomposers and vegetation both directly and indirectly. Carbon and nutrients are lost in stump and root biomass that is transported from the forest. Furthermore, stump harvesting operation disturbs soil heavily changing its physical structure and may have substantial consequences for carbon and nutrient reserves and mineralisation (Walmsley and Godbold 2010).

1.4 Effects of site preparation on vegetation and planted seedlings

The resulting effect of clear-cutting followed by site preparation is secondary succession in plants. Responses of vegetation to forest harvesting depend on the intensity of management practices and the amount and quality of residues left on site (see e.g. Olsson and Staaf 1995, Bråkenhielm and Liu 1998; Palviainen *et al.* 2005). The coverage of mosses and dwarf shrubs has been shown to decrease after clear-cutting, most likely due to the changes in microclimate (Keenan and Kimmins 1993, Jalonen and Vanha-Majamaa 2001, Bergstedt and Milberg 2001). Instead, many other plants, like narrow- and broad-leaved grasses and broadleaved trees, have been shown to increase with logging intensity (Bergstedt and Milberg 2001, Strandström 2006).

Clear-felled stands in Finland are mainly planted using nursery produced tree seedlings. For instance, every year more than 150 million seedlings are produced for planting in commercial nurseries in Finland (Ylitalo 2010). Planted spruce seedlings have been observed surviving better and growing faster after an intensive soil preparation, such as mounding, compared to lighter methods, such as disc trenching (see e.g. Saksa *et al.* 2005, Heiskanen and Rikala 2006, Uotila *et al.* 2010). Stump and slash removal after clear felling has been shown to have positive impacts on natural and artificial forest regeneration and tree growth (e.g. review by Vasaitis *et al.* 2008).

Most of the plants living in boreal forests form a symbiotic interaction with fungi existing in the rhizosphere of the plants. These mycorrhizal fungi are widespread and numerous, and all are symbiotic with a specific or a few plant species. Spruces, pines, firs and larches of boreal forests are associated with ectomycorrhizal (ECM) fungi, principally Basidiomycetes, that are able to enhance nutrient and water uptake by increasing the root-absorbing area and inhibit the influence of several pathogenic factors (Rudawska 2007, Smith and Read 2008, Lehto and Zwiazek 2011). The diverse community of mycorrhiza affects also positively on plant growth (Perry *et al.* 1987, van der Heijden *et al.* 1998, Rajala 2008). However, clear felling of boreal coniferous forests and following regeneration practices always change the mycorrhizal community of the site (see e.g. Jones *et al.* 2003, Heinonsalo et al. 2004). The conditions in the soil change: soil layers are mixed, temperature range becomes more extreme, the amount of radiation increases and the water table level increases as well. Site preparation changes the ECM community structure (Pennanen *et al.* 2005), and soil compaction and stump removal reduce the numbers and morphological types of ECM (Page-Dumroese *et al.* 1998). On the other hand, mineral soil has been shown to be an important reservoir of ECM (Rosling *et al.* 2003), which may secure the presence of ECM in the highly damaged soils.

1.5 Aims of the thesis

Life below ground is intimately linked to soil functioning and, consequently, to the integrity of terrestrial systems. Any artificial activity that changes the environmental and living conditions of soil organisms may affect the whole ecosystem functioning, both below- and aboveground.

Modern silviculture, including mechanical site preparation after final felling, causes substantial disturbance to the soil and the decomposer community that inhabit organic soil layers. Stump removal is likely to further increase the level of this disturbance. The large extent of habitat fragmentation and high amounts of low quality habitat (exposed mineral soil) in the areas, due to stump pulling and soil preparation procedures, have led to concern over system functioning and site productivity at the managed forest stands. Therefore, the main objective of the present thesis was to extensively determine the short-term effects of stump removal on soil decomposer and plant communities, carbon and nitrogen transformations and survival and growth of planted seedlings with their mycorrhizal associations in clear-felled boreal Norway spruce forests. Study sites prepared by mounding (stumps retained) were used as controls.

The specific questions were:

1. How do diversity and numbers of the most important decomposer animal groups, such as nematodes, enchytraeid worms and arthropods, and soil microflora of intact soil and exposed mineral soil respond to stump harvesting over time?

2. Does the succession of vegetation in stump harvesting areas differ from that in the traditionally treated clear felling areas?

3. Do the survival and growth of planted spruce seedlings and infections of their symbiotic partner ectomycorrhizal fungi differ between stump removal and mounding sites?

4. Are there any short-term differences in decomposition activity and nutrient dynamics between stump removal and traditionally prepared sites? And does the production of common greenhouse gases, CO_2, CH_4 and N_2O, differ in the differently treated clear-felled sites?

2 MATERIALS AND METHODS

2.1 Study sites

All study sites were located in central Finland. All together, 35 experimental stands, owned by UPM Kymmene and the city of Jyväskylä, were situated in Jyväskylä (62°12´N, 25°40´E), Lievestuore (62°15´N, 26°12´E), Juupavaara (61°52´N, 24°36´E) and Haukilahti (Jämsä-Orivesi region; 61°48´N, 24°47´E). During the study period, the annual mean temperature in the area was 4.9°C, and mean annual precipitation was 781mm. The permanent snow cover lasted approximately three months (Finnish Meteorological Institute). Soil in the areas is podzolised moraine with a 3-4cm thick organic layer.

Study sites were Norway spruce (*Picea abies* (L.) Karst.) dominated forest stands growing on Oxalis-Myrtillus (OMT) or Myrtillus (MT) site types (Cajander, 1949). On OMT site type, *Vaccinium myrtillus, Linnaea borealis, Oxalis acetosella, Maianthemum bifolium* and *Convallaria majalis* were the dominating field layer plant species, whereas on MT site type the dominating species are *V. myrtillus, V. vitis-idaea* and *L. borealis* (Hotanen *et al.* 2008). The sizes of the study sites varied between 0.5 and 4 hectares. From each site, 20 x 20m (400m^2; I) or 30 x 30m (900m^2; II, III and IV) study plots were chosen, from which soil samplings and vegetation surveys were carried out. Marshy, rocky and stony areas were avoided.

The experimental stands of all study sites (I – IV) were derived from common commercial clear-cuts. For the intact soil study (I), the sites were clear-felled in 2001, 2002 or 2004, and for the rest of the studies (II, III and IV) in 2002 or 2005. After clear felling, ca. 70% of the felling residues were collected from all the sites and stumps were removed from half of them using an excavator equipped with a special stump removal bucket. Soil was prepared by mounding in all sites (in the stump removal sites to ensure enough planting sites): the mounds were made with an excavator by inverting a scoop of soil on top of the soil nearby. All the management and regeneration practices performed in the study areas were done by the contractor chosen by the forest owner and according to the current prevailing forestry guidelines in Finland. In addition to the clear-felled sites, five similar, un-cut Norway spruce dominated forest stands from the Haukilahti area were selected for sampling to derive reference data for the effects of clear felling itself (II).

2.2 Experimental designs

2.2.1 Decomposer and plant communities in intact (I, II) and exposed mineral soils (II)

The concern about habitat fragmentation and the lower amount of high quality habitat (intact soil) first encouraged the study of decomposer community of the undisturbed forest floor patches (I). During the first years after soil treatments, these patches offer proper habitats for soil decomposers in an otherwise harsh environment of newly exposed mineral soil (Bengtsson *et al.* 1998, Rantalainen *et al.* 2004). These forest floor patches are also potential sources for later colonization of mineral soil, along with the accumulation of new organic matter (Siira-Pietikäinen *et al.* 2003a). The fifteen study sites (five sites clear-felled in 2001, five in 2002 and five in 2004) of intact soil study (I) contained both stump removal and traditionally site prepared (mounded) subareas. The soil was sampled for microflora (bacteria and fungi), nematodes, enchytraeid worms, collembolans and macrofauna. Since the clear-felled areas included both stump removal and mounding subareas, altogether 30 plots were studied in this paired samples study (I).

Since the degree of exposed mineral soil was observed to be high in the intact soil study (I), the focus of the second study was on the soil decomposer community and vegetation of both exposed mineral soil and intact forest soil. Here, the exposed mineral soil and intact soil was studied from both stump removal and mounded sites (II). Ten of the experimental stands were clear-felled in 2002 and ten in 2005. Stumps were removed from half of the study sites. There were five replicates in studies I and II in each treatment (stumps removed or left on site) and time (regeneration year) combinations. The sites/subareas with stumps were considered controls in these studies. Samplings were carried out twice, in spring and in autumn 2005 in the intact soil study (I), and three times in spring 2007, autumn 2007 and spring 2008 in the study of intact and exposed surfaces (II). In addition, soil properties, such as soil pH, moisture and organic matter contents and proportional areas of undisturbed and mineral soil surfaces, were measured from all the sites in both studies. Vegetation surveys were done twice, in 2007 and 2008, from the ground and field layers and both from intact soil and exposed mineral soil (II). In addition, the same decomposer community samplings and vegetation surveys, as done in study II, were conducted in the standing forests to get reference data from mature forests, but only from intact soil (these were, however, excluded from the statistical analyses).

2.2.2 Seedling growth and mycorrhizal infections (III)

The survival, growth and mycorrhizal infections of planted Norway spruce seedlings were compared between stump removal (100 seedlings) and mounding sites (100 seedlings). All ten study sites were clear-felled in 2005, after which the stump removal (five sites) and site preparation (five sites) were performed. All seedlings were 1.5 years old nursery seedlings planted on mounds in all study sites in May 2006, the following year after the clear cuts, stump removal and site preparation. In addition to the 200 planted seedlings, there were ten seedlings (1.5 years old) from the nursery garden that were just measured for the mycorrhizal infections. Seedlings height was measured right after planting and their growth was followed during three growing seasons. However, after two growing seasons, in autumn 2007 half of the seedlings (fifty from stump harvesting sites and fifty from mounding sites) were removed and their mycorrhizal infections were investigated. The following year, the remaining seedlings were removed and their mycorrhizal colonization was studied as well.

2.2.3 Nutrient dynamics in exposed mineral soil (IV)

The main objective was to determine whether the increased intensity of soil disturbance at the stump removal sites leads to increased mineralisation of carbon and nitrogen in the short-term, when compared to the mounding sites. The study sites were the same as in study II. Since the extent of the exposed mineral soil patches at the stump removal sites was higher than that at the mounding sites, the mineral soil surfaces exposed during the management (stump removal and/or mounding) practices were thoroughly studied. In addition, the fluxes of the most important greenhouse gases, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), from de-stumped and conventionally prepared soils were measured.

2.3 Analyses and Extractions

Several individual soil samples for each studied decomposer organism group were taken to a depth of 4cm with a steel soil auger (25cm2) from intact soil (I, II) and exposed mineral soil (II, IV). The soil animals were extracted, and soil properties, nutrient dynamics and microbial communities were analysed from the samples. Enchytraeids and nematodes were extracted from fresh soil samples using the wet funnel method (O'Connor 1962). Microarthropods were extracted using high-gradient extractor (dry funnels), in which temperature was continuously controlled. Mites were identified to family or superfamily level and collembolans to species. Macroarthropods were extracted using large dry funnels (described by Huhta 1972). After extraction, the animals were identified to family or order level depending on animal group. In addition, macroarthropods were classified to functional groups according to their feeding habits (see Persson *et al.* 1980). Herbivores included Aphididae, Coccoidea, Thysanoptera, Symphyta (Hymenoptera), Homoptera, Psylloidea, Curculionidae, Elateridae and Lepidoptera; microbivores large collembolans (Entomobryidae); microbi-detritivores Protura, and larvae of Diptera; and predators Araneae, Opiliones, Chilopoda, Neuroptera, Formicidae and most carabid beetles.

Soil moisture content was calculated after the subsamples had been dried more than 24 hours at +80ºC (I, II). The proportion of soil organic matter was determined as loss on ignition by heating subsamples at +550ºC for four hours (I, II, IV).

Microbial community structure (I, II) was determined using phospholipid fatty acid (PLFA) profiles. PLFA profile was determined for each sample following procedures described by Frostegård *et al.* (1993) and modified by Pennanen *et al.* (1999). The sum of all identified PLFAs was used to indicate the total microbial biomass. The sum of PLFAs considered to be predominantly of bacterial origin (i15:0, a15:0, i16:0, 16:1ω9, 16:1ω7t, i17:0, a17:0, 17:0, cy17:0, 18:1ω7 and cy19:0) was used as an index of the bacterial biomass (PLFAbact) (Frostegård and Bååth 1996). The quantity of 18:2ω6 was used as an indicator of fungal biomass (PLFAfung), since 18:2ω6 in soil is known to be of mainly fungal origin (Federle 1986) and it is known to correlate with the amount of ergostrerol (Frostegård and Bååth 1996), a compound found only in fungi.

Norway spuce seedlings were planted on mounds and their height measured (III) from the base of the seedling, four times. For morphotyping the mycorrhizal status of the seedlings (III), the trees were dug up from the sites and their root system washed. From the roots, the mycorrhizal morphotyping was done first as a visual estimate and later from morphotype samples as molecular DNA analyses, from which the obtained sequences were separated in denaturing gradient gel electrophoresis (DGGE, Bio-Rad, Hercules, CA, USA) using running parameters 75V, 60°C and 16h (Korkama *et al.* 2006). Further, obtained partial ITS sequences were manually checked and aligned using BioEdit Sequence Alignment Editor and identified by comparing them with sequences retrieved from databases of GenBank and UNITE (Kõljalg *et al.* 2005) using BLASTN algorithm.

Amounts of C and N in the microbial biomass (IV) were determined using the fumigation-extraction method, as described by Kanerva and Smolander (2007). To determine net N mineralisation and net nitrification (IV), soil samples were incubated in 125ml glass bottles at constant temperature (14°C) and moisture (60% of water-holding capacity, WHC) for 6 weeks, as described previously for humus samples (Kanerva and Smolander 2007). In the same incubations, aerobic C mineralisation (IV) was evaluated as CO_2-C production (Kanerva and Smolander 2007).

Gas fluxes from the soil (IV) were measured from the closed aluminium chambers placed in the field on exposed mineral soil. Measurements were done using plastic syringes during a 17.5-minute measurement period at five minute intervals (2.5, 7.5, 12.5, 17.5 minutes). The samples were then taken to the laboratory and analyzed for CO_2, CH_4 and N_2O concentrations within 24h hours by gas chromatography (GC conditions for CO_2 see Pietikäinen and Fritze, 1995 and for CH_4 and N_2O see Alm *et al.* 2007).

Microbial analyses (PLFA, I and II), molecular analysis for mycorrhiza (III) and incubations for C and N analyses, as well as the gas chromatograph analyses (IV) were performed at the Finnish Forest Research Institute, Vantaa.

2.4 Statistical analyses

In statistical analyses of decomposer and plant communities and nutrient dynamics (I, II, IV), the mean of the replicate samples represented each study site. The statistical analyses of the seedling growth and their mycorrhizal infections (III) were done using the original data. Effects of stump removal on the soil animals, microbial biomasses and soil properties data of the intact soil study (I) were tested using paired samples T-test. Whenever possible (I, II, III, IV), repeated measures analysis of variance (ANOVA) was used to find out differences between the spring and autumn samplings and among the different management years (effect of time elapsed since the treatments) and soil surface types (intact soil and exposed mineral soil). If there were interactions between the within and between subject factors in repeated measures ANOVA, the univariate ANOVA was used and each sampling occasion was analyzed separately. In the seedling – mycorrhizal study (III) the data was analysed using repeated measures nested ANOVA to avoid the possible influence of study sites and mounds on the actual treatment. All these analyses were performed using SPSS for Windows™.

To analyze the treatment effects on microbial community, the PLFAs, principal component analysis (PCA) (PC-ORD 5.10 software; McCune and Mefford 1999) was used (I, II). Community structure analyses for collembolans (II) and vegetation (II) were done using Non-metric Multidimensional Scaling (NMDS) and Multi-response Permutation Procedures (MRPP, Zimmerman *et al.* 1985; PC-ORD 5.10 software, McCune and Mefford 1999, McCune and Grace 2002). The NMDS "autopilot" mode of PC-Ord was used with medium thoroughness and with relative Sørensen (Bray Curtis) distance measure.

3 RESULTS AND DISCUSSION

3.1 Stump removal enlarges the extent of disturbance in boreal forest soils

Undoubtedly, modern forest regeneration operations already cause substantial disturbance to the forest floor and soil when compared to unmanaged forests, and stump removal creates additional effects on soil physical structure, chemistry and biology (see Walmsley and Godbold 2010). Indeed, stump removal significantly decreased the amount of undisturbed forest floor at the clear-felled sites (I, II). Approximately only 30% of the forest floor remained intact after stump removal, whereas over 60% of the soil surface at mounding sites was left undamaged (I, II). During stump harvesting, the major part of soil organic layer is seriously disturbed, turned upside down or mixed into the mineral soil. This fact evidently affects the overall impact of the stump removal at forest stand level, which is reflected in the whole forest ecosystem functioning.

Artificial disturbances, such as clear felling and stump removal, trigger the forest ecosystem into the early phase of secondary succession when the environment starts to recover from the disturbance. Compared to natural disturbances, caused by insect outbreaks, storms or mild fires, where biomass is not removed from the system, clear felling and related site preparation processes increase the amounts of nutrients and carbon that are lost from forest ecosystem and soon after clear felling (Palviainen *et al.* 2004). This loss is evidently larger when logging residues and stumps with main roots are also removed from the clear-felled areas. Particularly, these materials form a long-term source of carbon and nutrients in clear-cut coniferous forests by increasing the heterogeneity of the forest soils (Sucre and Fox 2009), thus offering habitats for more diverse organism communities.

During the short observation period of this study, removal of slowly decomposing wood material in stumps and main roots may not have the opportunity to influence soil nutrient dynamics yet. Thus, it is evident that greater and deeper penetrating soil disturbance is attributable to the possible differences in decomposer community, rate of nutrient mineralisation and primary production, for example, between the stump removal and mounding plots.

3.2 Responses of soil decomposer community to stump harvesting

Regardless of the major soil disturbance after stump harvesting, no functionally important taxa were lost from the decomposer community (I, II). Stump removal did not manifest itself as major changes in abundances of decomposer organisms, when undamaged forest soil in stump removal and mounding plots were studied (I, II; Table 1). Only some minor changes in soil microbe and animal abundances (I), especially in nematode (I) and enchytraeid (II) abundance, were observed due to the stump pulling procedure. In addition, the responses were more or less the same in exposed mineral soil (II). This indicates a resistance of the decomposer community to severe disturbance due to stump removal practice. There is also previous evidence that soil fauna of coniferous forests is quite insensitive to clear felling and other stand management practices (e.g. Setälä *et al.* 2000, Siira-Pietikäinen *et al.* 2001, Siira-Pietikäinen *et al.* 2003b). However, nearly all decomposer organisms were lower in abundance in exposed mineral soil than in intact soil (II; Table 2). Hence, when the larger amount of exposed mineral soil of stump removal sites is taken into account, the stump pulling procedure negatively affected the decomposer community.

Exposed mineral soil is a harsh environment for decomposers due to a shortage of resources and larger diurnal fluctuations in temperature and moisture compared to intact soil (Kubin and Kemppainen 1994, Siira-Pietikäinen *et al.* 2003a), and removal of organic matter has been shown to affect the soil food web even over a few decades (Bengtsson *et al.* 1998). At the stump harvesting sites, however, the soil organic layer is not totally removed from the area along management practices, but most of it is of lower quality for decomposers, as it is covered by mounds of mineral soil or dispersed mineral soil. Therefore, since there is much less habitat of high quality available for decomposers in stump removal areas than in traditionally prepared areas, populations of decomposers are smaller and more fragmented. Habitat fragmentation is considered the major threat for biodiversity nowadays. However, the metapopulation theory (Hanski 1999) suggests areas or populations that remain undamaged after disturbance act as sources to inhabit the disturbed areas (sinks) later when circumstances are more favourable. Intact soil left undamaged after clear felling, site preparation and stump removal seemed to contain enough decomposers and act as a source to help the resilience of the managed areas and exposed mineral soil from these major disturbances in both studies (I and II).

Stump removal affected microbial biomass similarly to mounding when biomass was calculated per soil organic matter (both in intact soil (I, II) and exposed mineral soil (II)) (Tables 1 and 2). Forest management practices have previously shown to have either negative (Pietikäinen and Fritze 1995) or negligible (Smolander *et al.* 1998, Siira-Pietikäinen *et al.* 2001) effects on soil microbes. In general, this study showed that when the larger area of exposed mineral soil (with lower organic matter content than intact soil) in the stump removal sites is taken into account, mounded areas had higher microbial biomass than stump removal areas (II). However, microbial biomass of exposed mineral soil was higher than biomasses in intact soil five years after the treatment (II, Table 2), which most likely explains also the increased N mineralisation in older sites (IV). The difference in microbial biomass may be important at the forest stand level for the soil nutrient dynamics and for the population densities of microbivorous animals (e.g. Wardle *et al.* 2004). Indeed, this study also showed that large collembolans, microbivorous macroarthropods, living on the soil surface in boreal forests, were more abundant in the traditionally prepared areas (I). These arthropods may also derive a large part of their nutrition from plant tissues (Chahartaghi *et al.* 2005), and thus smaller amount of intact forest floor in the stump removal areas evidently reduced their resources soon after the treatments.

TABLE 1 The effects of stump removal on total numbers of different decomposer organisms measured in the study I and II. The symbol 0 refers to no effects, - refers to negative effect, and + to positive effect.

	Effects of stump removal	
Organism group	Study I	Study II
Microbes –total biomass	+ or 0[a]	0
Nematodes	- or 0[a]	0
Enchytraeids	0	-
Mites	not measured	- or 0[a]
Collembolans	- or 0[a]	0
Macroarthropods	0	not measured

[a]Depending on the treatment year and sampling occasion

Nematodes (I) and enchytraeids (II) were the few soil faunal groups that were affected negatively by the stump removal (Table 1). In addition, their numbers were lower in the mineral soil than in the intact soil, a trend also observed by Sohlenius (1982) (Table 2). Therefore, these animal groups appeared to be sensitive to disturbances and, at the forest stand level, stump harvesting is likely to decrease their population sizes. Since enchytraeids are a keystone species in boreal forest decomposition processes, including nutrient mineralisation (Huhta *et al.* 1998, Laakso and Setälä 1999), their dynamics and performance in clear felling areas are of great importance. Nevertheless, the lower abundance of enchytraeids in the stump removal areas was not reflected in lower nutrient mineralisation and plant performance. However, evidence from a microcosm study (Haimi and Siira-Pietikäinen 2003) and a field experiment (Siira-Pietikäinen et al. 2003a), indicates that enchytraieds are able to maintain their populations and their functional importance in habitats with few resources, in mineral soil patches, for instance. Thus, higher amounts of exposed mineral soil may not necessarily decrease the importance of enchytraeids in the stump removal areas in the long run.

At the forest stand level, population sizes of microarthropods (collembolans and mites) were lower in the stump removal areas when the significantly lower numbers in the mineral soil than in the intact soil patches were taken into account (II, Table 2). In addition, the community structure of collembolans was clearly divergent on different soil surface types and can be clearly divided as r- and K-selected species according to the extent of disturbance in soil. The r-selected species are typical in unstable habitats where good colonization and efficient mating/reproducing abilities are favoured, while K-selected species are those that do better in more stable conditions (Begon *et al.* 2005). In general, in exposed mineral soil (the more disturbed surface) the r-selected species (species of Isotomidae and Symphypleona with long furca (the jumping organ) and good vision indicating good colonization ability and ability to find their food and mates easier) dominated the community, whereas on intact soil the K-selected species (species of Isotomidae, without furca and visual organs, and species of Neanuridae and Onychiuridae with smaller and more clumsy habitus, and species of Entomobryidae and Tomoceridae) were more abundant. This changed abundance and community composition may also have impacts on other decomposers and soil functioning since Taylor *et al.* (2010) recently showed that microarthopod biomass can be a driving factor steering the biomass of other soil fauna groups.

Although forest management practices change the arthropod community compared to mature forests (Greenberg and McGrane 1996), the disturbance has not seemed to affect the arthropod community of the soil. In this study (I), the total numbers of epiedaphic macroarthropods were unaffected by the stump removal although at functional group level (classified by the feeding behaviour) some transient differences between the stump removal and stump retaining plots were detected. Microbi-detritivores, the majority being larvae of dipterans, responded positively to the stump removal three years after the treatments (I), for example. High abundance of these larvae in the undisturbed patches of the stump removal areas may simply be due to less available resources for adult insects to lay eggs. All the observed responses among macroarthropods were short-term, and as a result the ecological consequences in the forest ecosystem obviously remained negligible.

TABLE 2 The responses of decomposer and plant communities to the large exposure of mineral soil (abundance in mineral vs. intact soil) measured in the study II. The symbol 0 refers to no effects, - refers to negative effect, and + positive to effect.

Organism group	Response
Microbes –total biomass	+ or 0[a]
Nematodes	-
Enchytraeids	-
Mites	-
Collembolans	-
Ground layer vegetation cover (%)	+
Field layer vegetation cover (%)	+ or - [b]

[a]Depending on the year and treatment
[b]Depending on the year

In mature forest, the abundance of enchytraeids was at the same level as in the mineral soil of clear cutting areas (II). This is mainly due to the increase of decomposable material after clear felling, which together with microbial growth positively affects the enchytraeid populations, whereas the amount of resources in mature forest does not change. Mineral soil and soil in mature forests seem to offer similar environmental conditions for enchytraeids to maintain their populations. The vegetation cover and the abundances of mites, nematodes and microbes were higher in mature forests, or more or less similar, as in intact soil of clear cut areas (II). These findings are approximately in line with the previous results by Huhta (1976) and Siira-Pietikäinen *et al.* (2001, 2003a, 2003b).

In disturbed areas, the soil organism dispersal, in space and time, has a role in ensuring continuity of organism community and, hence, the whole system functions. Therefore, dispersal is a possible factor making soil food webs resistant and resilient to disturbances and stress (Hedlund *et al.*, 2004). It seems that the intact patches left on stump removal sites were able to act as sources of decomposer organisms to ensure enough migration of soil decomposers, although the smallest organisms in soil are not able to colonize large areas within this relatively short time period that was observed in these studies. However, the thorough mixing of soil layers may have contributed enough habitat heterogeneity and resources for decomposers to exist in this rather harsh habitat of mineral soil, although clear changes in organic matter content were not discovered (I, II, IV). In addition, passive migration of soil fauna (by wind, water or phoretically) may have helped to colonize mineral soil.

Although less undamaged forest floor was available as habitats for soil decomposers in the stump removal sites, these fragments harboured quite similar communities compared to the fragments in the mounding sites.

3.3 Effects of stump removal on N and C dynamics in mineral soil

In general, stump removal is unlikely to cause serious direct nutrient losses due to the relatively low nutrient concentrations of stump wood (Egnell *et al.* 2007). The total volume of coarse woody debris was observed to decrease by 20% in our stump removal study plots (Rabinowitsch-Jokinen and Vanha-Majamaa 2010). Stumps represent, however, long-term carbon and nitrogen reserves in boreal coniferous forests after clear-cutting and they can be significant nitrogen sinks, potentially diminishing nitrogen leaching from the stand (Melin *et al.* 2009, Palviainen *et al.* 2010).

Since the degree of exposed mineral soil in stump removal sites was significantly higher than in mounding sites (I, II) and it covered the majority of the areas, the nutrient dynamics were studied in mineral soil (IV) where the risk of leaching is highest. Net nitrogen mineralisation and nitrification were clearly increased in the stump removal plots (IV), even after one year since the treatments. In addition, the total amount of N was higher in the stump removal sites than in the mounding sites (IV). The differences in soil acidity or amount of soil organic matter could not explain the observed differences in N transformations, as they did not differ between the treatments (IV). Clear-cutting increases net N mineralisation either by initiating net nitrification or increasing it in boreal forest ecosystems (Vitousek and Matson 1984, Dahlgren and Driscoll 1994, Smolander *et al.* 1998, 2001). More substantial soil disturbance by the stump removal procedure compared to mounding and/or differences in the microbial communities in the differently treated plots evidently contributed to this difference. Likewise, concentration of nitrate-N was higher in stump removal sites, but only two years after the treatments (IV). Nitrate-N (or part of it) is easily leached from the system; however, it could also be possible that mineralized nitrogen is readily immobilized by soil microbes or utilized by the recovering and developing vegetation (Vitousek and Matson 1984). Usually, the growth of vegetation, including the planted conifer seedlings, is not restricted by the availability of nitrogen during the first years after regeneration (Egnell 2011). Thus, it is unlikely that only sparse plants could utilize the excess nitrate nitrogen already one to two years after the disturbance, although this may be the case later, since the responses of ground and field layer vegetation were positive to the high amount of exposed mineral soil (II, Table 2). Staaf and Olsson (1994) observed elevated nitrate nitrogen concentrations after complete tree harvesting somewhat later than was observed in this study (IV), NH_4-N peaking during the first two years after the treatments and NO_3-N thereafter the next two years.

The soil C:N ratio was lower in the stump removal sites than in the mounded sites (IV). However, amount of organic matter or the total amount of C did not differ between the treatments (IV). Thus, the increased amount of nitrogen was obviously related to the stronger mixing of soil layers in the stump removal procedure. As the C:N ratio is usually lower deeper in the soil (Tamminen 2000), mineral soil lifted up from the deeper soil layers during the stump pulling procedure might have affected the C:N ratio and the amount of total nitrogen of the surface soils (IV). Nitrogen fixation by microbes was not very obvious due to aerobic conditions in our surface soils.

Carbon dioxide production was higher in the stump removal plots than in the mounded plots (IV). This difference between the treatments may also be attributed to more efficient mixing of soil layers in stump pulling procedure, as well as differences in the quality of soil organic matter and soil moisture, as these factors have been shown to influence soil respiration in previous studies (e.g. Mallik and Hu 1997, Smolander *et al.* 2005, Jaatinen *et al.* 2008). In autumn, the microbial biomass of mineral soil was higher in the older sites compared to younger ones (II, Table 2), which was also observed as a higher soil respiration (microbial CO_2 production) at the sites treated in 2002 than in sites treated 2005 (IV). Developing vegetation could have produced more resources of better quality (litter and root exudates) for higher microbial biomass in the mineral soil patches during that three years period, although the total amount of organic matter was not increased.

The soils, in both treatments, appeared to be methane sinks (IV). Emissions of nitrous oxide were small, as was also found for other well drained forest soils (Von Arnold *et al.* 2005, Tate *et al.* 2006, Matson *et al.* 2009) (IV). Although the gas measurement data were limited (IV), it can be concluded that excluding CO_2 stump removal seems to not significantly affect the flux rates of the most common greenhouse gases previously observed in boreal forests (Tate *et al.* 2006, Matson *et al.* 2009). However, the increased CO_2 production in soil at stump removal sites (IV), in addition to the results of the modelling study of Repo *et al.* (2010), indicates that the amount of carbon dioxide released into the atmosphere through burning or soil respiration supports the concern regarding whether the removal of stumps and the disturbance caused by the removal procedure is acceptable for the balances of greenhouse gases.

3.4 Effects of stump removal on vegetation and planted Norway spruce seedlings

Plant community structure clearly changed with time after treatments and also differed between the two soil surface types (II). The greater quantities of exposed mineral soil in the stump removal sites, compared to mounding ones, offers suitable habitat for plant seeds to be trapped in and helps the colonization of plants. This is due to more favourable physical conditions for germination and early development of seedlings, and absence of competition for nutrients and space with the established vegetation (Crawley 1997). In addition, greater soil disturbance in the stump removal areas lifts the seeds present in the soil seed bank closer to the soil surface and increases their germination. Generally, groundcover vegetation was higher on the exposed mineral soil than on the intact patches, where most mosses died after the clear felling due to drastic changes in the environmental conditions (II, Table 2). Stump removal itself increased the cover of the field layer vegetation and the plant diversity as a whole (II), which is in line with previous findings that clear felling (site management) increases the species richness of vascular plants (see e.g. Bråkenhielm and Liu 1998, Bergstedt and Milberg 2001, Pykälä 2004, Widenfalk and Weslien 2009). Occurrence of dwarf shrubs *Vaccinium myrtillus* and *V. vitis-idaea* was lower in the stump removal sites than in the mounded sites, whereas *Rubus idaeus* significantly benefitted from the more severe disturbance due to stump pulling procedure (II).

Height of planted spruce seedlings did not differ between the stump removal and mounding sites after three growing seasons although their mean growth was approximately 10% higher at the stump removal sites (III). This supports the earlier findings that seedling survival, and especially their growth, has benefitted from stump removal (Vasaitis *et al.* 2008, Menkis *et al.* 2010). On the other hand, stump removal has also been observed to pose a 20% reduction in the conifer seedling height (Page-Dumroese *et al.* 1998). The growth response of the seedlings may vary depending on the time period and focal tree species, but also due to nutrient status of the site, degree of the site preparation intensity, and quality and quantity of harvested material. Stump removal procedure, however, substantially disturbs soil structure that promotes nutrient mineralisation (IV) (Johansson 1994, Lundmark-Thelin and Johansson 1997).

Norway spruces, like many other trees of boreal forests, live in symbiosis with ectomycorrhizal (ECM) fungi. Clear felling, site preparation and exposure of mineral soil have been shown to affect external mycelia of mycorrhizal fungi (Jones *et al.* 2002), and mycorrhiza has been expected to have positive effects on seedling viability (e.g. Kropp and Langlois 1990, Menkis e*t al.* 2007, Smith and Read 2008). Here, neither the seedling survival, nor the community composition of ECM fungi differed between the treatments (III). The high ECM colonization rate in the nursery seedlings was still detectable in the planted seedlings after two and three growing seasons and may at least partly explain the high survival of the seedlings (III). The seedlings were largely colonized by nursery fungi (mainly by *Thelephora terrestris*) rather than by ECM native to the planting site (III). Some increment in the ECM diversity during the study (III) was, however, observed, which supports the hypothesis that high fungal diversity enhances the nutrient and water uptake of the plants and, hence, the plant growth (Perry *et al.* 1987, Jonsson *et al.* 2001). However, the higher seedling growth and ECM colonization (fungal species other than *T. terrestris*) were only detected after one particular growing season and seemed to be transient. This may be due to the fact that stump and felling residue removal after clear felling are likely to increase decomposition and nutrient availability and, thus, decrease the need for seedlings to support ECM (Menkis *et al.* 2010). The importance of soil animals cannot be underestimated in helping the mycorrhiza spread through the environment (Klironomos and Moutglis 1999, Seres *et al.* 2007), further supporting the importance of diversity for ecosystem functioning.

Regardless of the higher amount of total N and mineralized N after stump removal (IV), the total nutrient losses after stump removal are evidently higher than those after clear felling without stump removal (Palviainen 2005, Palviainen *et al.* 2010). The ecosystem functioning, for example in primary production, is not necessarily affected during the first growing seasons of the next tree generation due to the higher net N mineralisation rates at the stump removal sites (IV). Although most of the tree biomass has been harvested from the clear-felled sites, there still is ample decomposing biomass left on site and severe soil disturbance also increases nutrient mineralisation (IV) (Johansson 1994, Lundmark-Thelin and Johansson 1997). Indeed, Örlander *et al.* (1998) showed that the site preparation improved seedling growth. The early growth of planted seedlings is favoured at managed sites, especially in the case when the seedlings are planted on mounds and seedling roots are associated with ectomycorrhizal fungi (Örlander *et al.* 1990, Allen 1991, Smith and Read 2008, Lehto and Zwiazek 2011).

3.5 Future concerns related to environmental impacts of stump harvesting and remarks of the thesis

Large amounts of nutrients and carbon are lost from forest ecosystems in clear felling as the biomass is removed from the sites (Palviainen *et al.* 2004). Stem-only harvesting leaves a greater proportion of deadwood in forests compared to the removal of felling residues and stumps (Walmsley and Godbold 2010). Deadwood has been considered an important resource for numerous kinds of organisms. In Finland alone, 4000-5000 species, including macrofungi, insects, other invertebrates, lichens, myxomycetes, bryophytes and vertebrates, are estimated to depend on deadwood as their habitat or resource (Siitonen 2001). Stumps may be the only source of large deadwood in clear felling areas, forming a crucial resource for many organisms and being an important stock of carbon. If up to 80% of the deadwood remaining on clear-cuts is in stumps (as was estimated by Hjältén *et al.* 2010) is removed, it evidently affects the organisms dependent on large deadwood. It is not enough, from the diverse ecosystem point of view, if only 4 - 6% of stumps are left on site as the new forestry instructions states (Äijälä *et al.* 2010). On the other hand, Eräjää *et al.* (2010) recently found that fine woody debris (small branches and pieces of wood, diameter less than 10cm) is actually more abundant in managed boreal forests than previously thought, and may turn out to be an important source of deadwood. However, in clear-cuts harvested for forest fuel, there were 42% less branches and 81% less stumps than in control clear-cuts (Eräjää *et al.* 2010). Additionally, Rabinowitsch-Jokinen and Vanha-Majamaa (2010) showed that the amount of coarse woody debris (CWD) was significantly lower at the stump removal sites than at the mounding sites.

In light of global warming, soils are carbon stores which act as sinks to prevent the increase in atmospheric CO_2. Recently, it has been estimated that stump harvesting may increase the release of CO_2 through acceleration of decomposition of organic matter not only in surface soil layer, but also in deeper soil layers accelerating the decomposition of so called old carbon stores (Walmsley and Godbold 2010). As podzolized soil profiles with thick humus layer have developed over hundreds of years, redistribution of the soil layers may have serious impacts on the fate of old organic carbon and nutrients. In addition, soil organic matter has an important role in site productivity in future forest rotations since it affects bulk density, water holding capacity, microbial populations and cation-exchange capacity of the soil (Johnson 1992). Vertical mixing of plant-derived material into the deeper mineral horizons due to forest management practices accelerate the CO_2 emissions from soil by physical or chemical destabilization or through the increase of microbial respiration in deeper soils (Zummo and Friedland 2011), which challenge the idea that wood biomass is a carbon neutral energy source.

Although this study showed that stump removal sites are not increasing the emissions of the two common greenhouse gases (CH_4 and N_2O) to the atmosphere (IV), it is important to acknowledge the amount of carbon bound in stumps itself. In the beginning of the energy production, the total amount of carbon emissions from burning forest biomass (including stumps) for energy is comparable to the emissions released in fossil fuel burnings (Repo *et al.* 2010, Liski *et al.* 2011). The average of indirect emissions per unit of energy produced has decreased over time since the beginning of bioenergy production. The indirect emissions depend, however, on the decomposition rate of harvested material, larger-sized woody litter (stumps) having lower decomposition rates than smaller sized residues. For example, using the stumps as energy production decreases the carbon emissions by 20% during the first 20 years, since the start of the production, compared to the emissions from charcoal burnings. Residue burnings instead decreases the emissions 50-60% compared to charcoal during the same time (Liski *et al.* 2011).

Further, it is possible that the acceleration of nitrogen mineralisation in the stump removal plots have consequences on site productivity later in the future. Stumps left on site after clear felling are known to act as sinks of N during their decomposition (Melin *et al.* 2009, Palviainen *et al.* 2010). The larger extent of exposed mineral soil in the stump removal plots increases the risk of nitrogen losses. Leaching of nitrogen would be even higher in the stump removal sites if felling residues were left on site (Staaf and Olsson 1994). It has been shown that already the whole tree harvesting (WTH) negatively affects the second rotation forest productivity (Walmsley *et al.* 2009). Reduction in nutrients at WTH sites showed that WTH decreased volume increment of trees compared to stem only harvesting (CH) (Helmisaari *et al.* 2011). Accordingly, the more the logging residue was harvested the more the relative volume increment decreased, emphasizing the importance of leaving the nutrient-rich needles on site (Helmisaari *et al.* 2011). Slowly decomposing logging residue guarantees stable availability of nutrients and, therefore, conclusions on the effects of logging residues and stumps on site productivity should be based on long-term studies rather than studies lasting only a few years after the removals (Wall 2008, Helmisaari *et al.* 2011)

The studies of this thesis were carried out in common commercial forests, where all the management practices were done by forestry companies according to current forestry guidelines. Many of the variables or characteristics of the study sites, such as the exact area of the site, exact amount of residue left on site, number of removed and retained stumps, amount of removed stems or volume of removed stems and amount of exposed mineral soil could have been controlled more carefully if the study setup and the implementation would have been done under strict control and by oneself. However, the results derived from this thesis reliably represent the current ecological conditions of Finnish commercial forests.

4 CONCLUSIONS

This thesis has extensively showed that the short-term effects of stump removal on forest ecosystem structure and functioning, the main ecological and environmental concerns, do depend on the amount and the degree of mineral soil exposed during the stump removal procedure. In the long run, the larger amount of wood material lost from the clear-cut area in stumps may produce changes in forest biota, as less deadwood is available for organisms.

Stump harvesting by itself had only minor short-term impacts on decomposers present in soil habitats (mineral and intact soil). However, since the abundance of decomposers was consistently lower in the exposed mineral soil than in the intact soil and because there was much more exposed mineral soil in the stump harvesting areas, stump harvesting has the potential to have a significant impact on decomposition processes and nutrient dynamics at the forest stand level. There was still redundancy in the soil after stump removal, as all functionally important taxa survived after the disturbance. Hence, the forest ecosystem is assumed to function properly although changes in nitrogen mineralisation may occur, as was shown in this thesis. The most important impact of the stump removal procedure on soil carbon and nitrogen dynamics is the broad mixing of soil layers that occurs during stump harvesting. Thus, clear acceleration of nitrogen mineralisation and few smaller differences between the treatments found in the exposed mineral soil, together with changed decomposer community structure, may manifest themselves at the forest stand scale. Therefore, all efforts to lower the degree of soil disturbance would be beneficial for the decomposer community and, hence, the nutrient retention and transformation in the stand. Now, the increased net N mineralisation and nitrification at the stump removal sites might at least partly enhance N leaching from the system. On the other hand, higher N concentration in stump removal sites was also revealed as higher primary productivity indicating that the overall vegetation development of clear-cut forest is somewhat different after stump removal than after traditional site preparation (mounding).

In addition, the observed increased evolution of CO_2 from stump removal sites, due to more intensive mixing of the soil layers, could lead to increased atmospheric carbon loading from soil detrital pools, linking soil biogeochemical processes to climate change.

Stump removal had some positive effects on the performance of planted spruce seedlings. The overall mycorrhizal colonization of the seedlings was very high already at planting and this was obviously a significant factor causing the high survival and good growth of the seedlings. The diversity of ECM community increased in the field during the first years and it is possible that circumstances for the development of the seedlings and mycorrhiza were very suitable both at the mounded and stump removal sites, possibly due to the decreased competition between the tree seedlings and the other vegetation on the mounds. Since stumps are located partly belowground it can be expected that they could harbour more abundant ECM fungi than decaying logs that have been found to contain ectomycorrhizal fungi already at an early stage of decomposition. Thus, the potential impacts of stump removal on the richness of symbiotic fungi will manifest themselves considerably later than in the time scale of this study.

It should also be kept in mind that stumps are the major long-term source of deadwood in the clear-felled stands, and the effects of stump removal on biodiversity and ecosystem processes, as well as the development of the next tree generation may become significant. Increasing the intensity of the harvestings of forest biomass for bioenergy production can only be based on results derived from carefully designed forest stand scale experiments.

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YHTEENVETO (RÉSUMÉ IN FINNISH)

Kantojen korjuun vaikutukset metsämaaperään ja kasvillisuuteen

Kantojen korjuu on viimeisen vuosikymmenen aikana voimakkaasti yleistynyt menetelmä tuottaa uusiutuvan energian raaka-ainetta, puuhaketta. Viimeaikaiset ilmastotavoitteet ja päästökauppa ovat osaltaan vielä lisänneet metsistä ja nimenomaan kannoista saatavan hakkeen käyttöä. Aikaisemmin kantoja on nostettu juurikäävän vaivaamilta alueilta lähinnä siksi, ettei juurikääpä leviäisi uudistusalalla puihin jo taimivaiheessa. Hakkeeksi kantoja korjataan, ainakin vielä toistaiseksi, pääasiassa kuusivaltaisista metsiköistä pian päätehakkuun jälkeen. Vaikka tuoreet metsänkäsittelyohjeet (vuodelta 2010) sisältävät luonnon monimuotoisuuden huomioonottamisen ohjeita myös kantojen korjuualoilla, ja ohjeita siitä kuinka paljon ja minkä kokoisia kantoja hakkuualalle on jätettävä, kantojen korjuu muokkaa metsämaisemaa ja –maaperää huomattavasti enemmän kuin perinteinen avohakkuu ja sitä seuraava maanmuokkaus metsikön uudistamista varten. Kantojen korjuualalla useat työkoneet toisaalta tiivistävät maata ja toisaalta kannonnoston seurauksena myös rikkovat laajalti maanpintaa. Kantoja nostetaan keskimäärin 400 - 600 kappaletta hehtaarilta. Maanpinnan paljastumisesta huolimatta kannonnostoaloilla on kuitenkin tarpeellista tehdä vielä maanmuokkausta metsän uudistamista varten. Uudistusaloille istutetaan puulajista riippuen 1600 – 2000 tainta hehtaaria kohden.

Boreaaliselle havumetsälle tyypillisen humuspitoisen metsämaan kehittyminen on vienyt useita satoja, ellei jopa tuhansia, vuosia. Maaperällä on tärkeä tehtävä kasvien kasvualustana ja toisaalta toimintakykyisen hajottajaeliöyhteisön ylläpitäjänä. Hajottajat hajottavat kuolleen orgaanisen aineen (kuten kuolleet kasvinosat) ja viime kädessä vapauttavat siihen sitoutuneet ravinteet käyttökelpoisessa muodossa jälleen kasvien käytettäviksi. Tämä metsäekosysteemin tuottama ravinteiden kierrätys–palvelu ja siihen mahdollisesti kohdistuvat häiriöt vaikuttavat mm. tulevien puusukupolvien kehitykseen. Kantojen nosto on siis astetta voimaperäisempi häiriö metsikön maaperälle ja sen eliöstölle kuin perinteinen laikkumätästys, jossa maanpinta rikkoontuu pääsääntöisesti vain laikkujen kohdalta ja maa tiivistyy vähemmän kun työkoneiden liikkuminen aloilla on vähäisempää.

Tämän tutkimuksen tavoitteena oli tuottaa uutta tietoa siitä miten kuusivaltaisen boreaalisen havumetsän avohakkuun jälkeinen kannonnosto vaikuttaa metsämaaperän hajottajaeliöstöön, hiilen ja typen dynamiikkaan sekä kasvillisuuden ja istutettujen kuusentaimien sekä niiden sienijuurien alkukehitykseen ensimmäisinä vuosina käsittelyiden jälkeen. Kannonnostoaloja verrattiin perinteisesti laikkumätästettyihin aloihin. Tutkimusaloilla käsittelyjä (kannonnosto ja laikkumätästys) oli tehty useampana eri vuonna, ja toisaalta aloja tutkittiin useamman vuoden ajan, jolloin saatiin vertailu- ja seurantatietoa siitä miten hajottajaeliöyhteisö, kasvillisuus ja taimet kehittyvät laikkumätästetyillä aloilla ja aloilla joilta kannot oli nostettu. Tutkimusalojen maaperästä mitattiin myös orgaanisen aineen pitoisuutta, pH:ta ja maa-aineksen kosteutta. Lisäksi alojen rikkoontuneen ja ehjäksi jääneen maanpinnan osuudet arvioitiin. Tutkimusaloilta kerätyistä ehjän maanpinnan ja paljastuneen mineraalimaanpinnan maakairanäytteistä selvitettiin hajottajaeliöiden lukumääriä ja yhteisöjen rakennetta sekä hiilen ja typen ravinnedynamiikkaa maaperän ylimmän 4 cm:n syvyydeltä. Kasvillisuuden ja tutkimusaloille istutettujen kuusentaimien kehittymistä seurattiin useamman kasvukauden ajan. Tutkimusjakson lopussa tutkimustaimet kaivettiin maasta ja niiden juuristo tutkittiin laboratoriossa sienijuuri-infektioiden kartoittamiseksi.

Tulokset osoittivat, että maanpinta rikkoontuu ja kivennäismaata paljastuu 2-3 kertaa enemmän kannonnostoaloilla kuin perinteisesti käsitellyillä laikkumätästysaloilla. Kannonnosto vähensi selvästi sukkula- ja änkyrimatojen lukumääriä, mutta muissa hajottajaeliöryhmissä erot käsittelyiden välillä (jos niitä yleensä edes oli) olivat pieniä ja lyhytaikaisia. Rikkoontuneella maanpinnalla (mineraalimaa) oli kuitenkin merkittävästi vähemmän kaikkia tutkittuja hajottajaeliöyhteisön edustajia kuin maanäytteissä, jotka oli otettu käsittelyissä ehjäksi jääneeltä maanpinnalta. Lisäksi mikrobi-, hyppyhäntäis- ja kasviyhteisöt erosivat selvästi paljastuneen mineraalimaan ja ehjän maanpinnan välillä.

Huomionarvoista on, että koska kannonnostoaloilla mineraalimaata paljastuu huomattavasti enemmän ja koska sillä eliöitä oli merkittävästi vähemmän kuin ehjäksi jääneellä pinnalla, vaikuttaa kannonnosto metsikkötasolla vähentävästi maaperäeliöyhteisöön. Tämä voi pitkällä aikavälillä vaikuttaa mm. ravinnekiertoon, kuten muuttunut typen (N) kierto osoitti; kokonaistypen määrä, typen nettomineralisaatio ja nitrifikaatiopotentiaali olivat suurempia kannonnostoaloilla kuin laikkumätästetyillä aloilla. Sen sijaan tällä lyhyellä tutkimusaikavälillä hiilen (C) osalta muutoksia ei selvästi havaittu. C:N-suhde kannonnostoaloilla oli jopa jonkin verran pienempi kuin laikkumätästetyillä aloilla, mikä kertoo kannonnostoalojen olevan hajottajaeliöstölle resursseiltaan parempilaatuinen, mutta se kertoo myös voimakkaammasta maanpintakerrosten sekoittumisesta ja typen huuhtoutumisriskin kasvusta kannonnostoaloilta. Maaperän pH:ssa ja orgaanisen aineen määrässä ei havaittu mainittavia eroja eri käsittelyiden välillä. Kannonnostoalojen verrattain korkea vapaan nitraattitypen määrä selittänee aloilla runsaampana esiintyvää kenttä- ja pohjakerrosten kasvillisuutta käsittelyjen seurauksena muuttuneen mikroilmaston lisäksi. Kasvillisuuden lajimäärä oli myös korkeampi kannonostoaloilla mikä johtunee laajemmalti paljastuneesta mineraalimaasta, jolla siemenet itävät paremmin kuin kasvillisuuden peittämässä maassa, ja toisaalta siemenpankin aktivoitumisesta, kun maa muokkautuu voimakkaammin. Varpukasveista mustikka ja puolukka sekä sammaleista seinäsammal ja kynsisammalet vähenivät selvästi ja siten kärsivät kannonnostosta, kun taas vadelma hyötyi siitä. Maisemassa myös koivu näkyi selvästi hyötyneen kannonnostosta sillä koivutaimikko oli erittäin tiheää kannonnostoaloilla muutaman vuoden kuluttua uudistamisesta.

Maanmuokkauksen tuloksena syntyneille mättäille istutetut kuusentaimet kasvoivat hyvin sekä laikkumätästetyillä että kannonnostoaloilla, kasvu oli kuitenkin ensimmäisten kahden kasvukauden jälkeen n. 10 % nopeampaa kannonnostoaloilla. Taimet infektoituivat tehokkaasti luontaisesti symbionttisilla sienillä jo taimitarhoilla. Kuolleisuus tutkimustaimilla olikin hyvin pientä (4 – 8 % koko kolmen vuoden tutkimusjaksolla), joka voi osin selittyä sillä, että taimien juuristot olivat lähes sataprosenttisesti sienijuurten eli mykorritsojen kolonisoimia. Kahden kasvukauden jälkeen kannonostoalojen kuusentaimien kasvun havaittiin korreloivan negatiivisesti karvasilokan (*Thelephora terrestris*, ylivoimaisesti yleisin havaittu sieni) kolonisoitumisasteen ja positiivisesti muiden sienien (kuin karvasilokan) kolonisoitumisen kanssa. Tämä positiivinen riippuvuus muista kuin yleisimmästä sienijuuresta tukee oletusta siitä, että monimuotoisempi symbionttinen sienijuuriyhteisö parantaa kasvien (tässä tapauksessa kuusentaimien) kasvua.

Väitöskirjatutkimukseni osoitti, että lyhyellä aikavälillä maan pinnan laajemmalla paljastamisella ja maan sekoittumisella on suurempi vaikutus metsäekosysteemin toimintaan kuin itse kantojen poistolla. Lyhyellä aikavälillä kannot resurssina eivät vielä näytä vaikuttavan maan hajottajaeliöstöön tai ravinteiden varastoitumiseen. On kuitenkin syytä huomioida kasvanut hiilidioksidin tuotanto kannonnostoalojen laajalla mineraalimaapinnalla, joka kertoo maan mikrobiston aktiivisuuden lisääntymisestä aloilla. Voimakkaampi maanmuokkaus edesauttaa mikrobiston toimintaa, ravinteiden vapautumista, myös hiilen vapautumista ja siten mm. perustuotantoa. Mineraalimaan paljastumisen vähentäminen metsänkäsittelyjen yhteydessä voi auttaa metsäekosysteemiä palautumaan nopeammin sitä kohdanneesta häiriöstä ja toisaalta vähentää nyt todettua ravinteiden mahdollista huuhtoutumisriskiä pidemmällä aikavälillä.

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