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Effects of stump harvest and site preparation on N_2O and CH_4 emissions from boreal forest soils after clear-cutting ☆

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ABSTRACT

Harvesting stumps after clear-cutting can increase bioenergy supplies and thus reduce needs for fossil fuels, but more knowledge is required about associated changes in greenhouse gas emissions from forest soils to assess the climatic impact of extracting stumps for this purpose. The soil disturbance caused by harvesting stumps may alter soil processes, including N mineralization. N availability is an important determinant of emissions of the potent greenhouse gases N_2O and CH_4. Effects of stump harvest on these gases are largely unknown. Therefore, they were explored in this study by monitoring differences in N_2O and CH_4 emissions associated with different types of disturbance during two years following stump harvest and site preparation (as well as their overall effects) at three mesic sites, using the chamber technique. N_2O emissions at two of the sites were affected by the type of soil disturbance, but not at the other site. At one site, the N_2O emissions were highest from undisturbed soil and mounds and significantly lower from mixed soil, bare mineral soil and wheel ruts. At this site the emission rates were clearly correlated with N availability across the disturbances. At the second site showing significant treatment effects, N_2O emissions were higher from the bare mineral soil after site preparation than from other types of disturbed soil. At the third site there were no significant N_2O emissions, possibly due to reductions in nitrogen availability caused by the fast establishment of vegetation at that site. The CH_4 fluxes included both uptakes and losses, but were generally low following all types of soil disturbances, although they were substantial from wheel ruts and soil pits. In conclusion there were no, or minor, between-treatment differences in N_2O and CH_4 emissions. Furthermore, the radiative forcing potential of these emissions was small compared to mean CO_2 emissions from Swedish clear-cuts. Thus, our results indicate that stumps can be harvested without causing elevated emissions of N_2O and CH_4 on mesic sites. The effects on wetter sites remain to be illuminated.

1. Introduction

Forests and forestry can play potentially significant roles in combating climate change, by both increasing the carbon storage in forest ecosystems and substituting woody biomass for fossil carbon in fuels and materials (Canadell and Raupach, 2008). However, there is increasing pressure on forest resources, and many services from the forest are conflicting or mutually exclusive. For example, using wood for bioenergy reduce supplies for making other timber products. Harvesting stumps after clear-cutting is advantageous in this respect, as it can increase bioenergy supplies and thus reduce the need for fossil fuels without threatening supplies of raw material for traditional forestry products like paper and construction wood. Stump harvest is a new practice with old traditions in various northern European countries, such as Finland, Lithuania, Sweden and the UK (Hannam, 2012). It has also been practiced in Canada and US, but mainly there to suppress root rot (Hannam, 2012; Cleary et al., 2013). However, in northern Europe stump harvest has been previously practiced only at small scale and the environmental effects of large-scale implementation, as being considered now, have been insufficiently studied (Swedish Forest Agency, 2009; Swedish FSC, 2011; Persson, 2012; Walmsley and Godbold, 2010). In particular, more knowledge is needed about stump harvesting effects on green-house gas balances.

Besides carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) are the most important green-house gases that are emitted

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from forest ecosystems and thus may be influenced by forest management practices. Both gases are produced by microorganisms under anoxic (CH_4) or hypoxic conditions (N_2O). Methane emission from soils to the atmosphere is a dynamic result of methanogenesis minus methanotrophy, microbe processes that can occur simultaneously in the same soil profile, producing and consuming CH_4, respectively (Le Mer and Roger, 2001). The processes that can generate N_2O are denitrification and nitrification (Nömmik, 1956). N_2O is one intermediate in the complex steps of denitrification (Myrold, 1998). In the last step of denitrification N_2O is reduced to N_2 by N_2O reductase. In comparison to other enzymes involved in the denitrification process it is more easily inhibited by oxygen and sensitive to low pH. Thus, more N_2 is produced in this step during anoxic conditions and at higher pH. The N_2O production during the nitrification, though, is promoted by oxic conditions. Therefore, N_2O production in soils is controlled by variation in oxygen condition (Schlesinger, 1997). A prerequisite for nitrification and denitrification, are also availability of ammonium (NH_4) and nitrate (NO_3) ions and higher availability can increase N_2O emissions (Christiansen and Gundersen, 2011; cf. Gundersen et al., 2012). Availability of NH_4 and NO_3 in soils of boreal and hemi-boreal forests is generally highest following disturbances (Tamm, 1991; Vitousek et al., 1979; Vitousek and Melillo, 1979), and significant emissions of N_2O are therefore most likely to occur during the first ca 5 years following harvests. Observations of elevated N_2O emissions have also been reported after final harvest followed by site preparation (Saari et al., 2009). Harvesting may also increase CH_4 emissions by raising ground water levels and increasing the abundance of soil organic matter, which includes substrates for methanogenesis (Zerva and Mencuccini, 2005; Wu et al., 2011; Sundqvist et al., 2014). The potential increases in N_2O emissions are likely due to increases in soil moisture and nitrate availability (Staaf and Olsson, 1994; Davidson, 1995; Saari et al., 2009).

Stump harvesting in the Nordic countries currently involves use of an excavator equipped with a device for splitting and lifting stumps and coarse roots (Routa et al., 2013). The stump lifting in combination with the damage caused by excavators and forwarders results in various kinds of soil disturbance (Strömgren et al., 2012; Tarvainen et al., 2015). The areal extent and severity of this damage depends on the physical stability of the soil, which varies with the ground water level (normally elevated following final felling), season and soil texture (Berg, 1982; Ågren et al., 2014) and the technique used (Berg et al., 2015). Site preparation is a standard procedure after final harvests in northern European forestry that is intended to enhance the new seedlings' establishment and growth (Swedish Forest Agency, 2014; Mjöfors, 2015). Since stump harvesting may reduce, but not always completely exclude the need for site preparation, it is often complemented with site preparation (Rantala et al., 2010). Although site preparation and stump harvesting have similar effects, the latter removes coarse roots, may reduce soil stability and cause more severe soil disturbance than site preparation alone (Walmsley and Godbold, 2010; Strömgren et al., 2012). For example, combining stump and coarse-root harvesting with site preparation by mounding may increase the area of disturbed soil from 25% to 50% of a total harvested area, following mounding alone, to 70–80% (Kataja-aho et al., 2012; Saksa, 2013; Strömgren and Mjöfors, 2012; Mjöfors, 2015; Tarvainen et al., 2015).

Soil disturbance from stump harvesting and site preparation potentially alters soil conditions which can affect both production and transmission of CH_4 and N_2O. Sundqvist et al. (2014) found higher emissions of CH_4 from disturbed areas on a clear-cut after site preparation and/or stump harvesting and Booth et al. (2006) found that mixing of soil generate N_2O production in an *in vitro* study. As stump harvesting cause more severe soil disturbance than site preparation, it is also likely to cause higher emissions if soil mixing stimulates CH_4 and N_2O production. However, the combinations of various types of soil disturbance at a clear-felling add complexity. For example, CH_4 production may be stimulated in the frequently moist or water-filled ruts created by heavy machinery's wheels (Teepe et al., 2004), but soil compaction in wheel ruts may also reduce gas transmission from soil to the atmosphere. Furthermore, significant fractions of inorganic N may be microbially immobilized in stump and root systems after conventional harvesting (Palviainen et al., 2010; Bergholm et al., 2015). Both stumps and roots have low N content (Hellsten et al., 2013), which restricts the rate of decomposition, and to increase decomposition and growth, certain wood-living fungi can import N from organic matter with high availability of N e.g. needle litter (Staaf and Berg, 1982). Palviainen et al. (2010) observed that the amount of N in spruce stumps still were 2.7 times the initial N amount after 40 years, showing that stumps and roots can be N sinks for a long time. In line with this observation, increased concentrations of inorganic N in soil water (Staaf and Olsson, 1994) and total N in runoff water (Eklöf et al., 2012) following stump harvest has been demonstrated. Hence, there is a risk that stump harvest may lead to higher concentrations of inorganic nitrogen in the soil, and thereby enhance the N_2O emissions.

Because N_2O emissions from boreal forest soils are likely to be weaker than those from soils of other, more productive (e.g. arable) ecosystems, relatively little attention has been paid to denitrification in boreal soils and, to our knowledge, no studies on N_2O emissions and only one regarding CH_4 emissions (Sundqvist et al., 2014) following stump harvest have been published. Sundqvist et al. (2014) measured CH_4 fluxes in an undisturbed forest and on a clearcut subjected to mounding in one part and stump harvest in the other part. They observed the highest CH_4 emissions from points of "bare soil where organic and mineral soil were mixed" either after site preparation or stump harvest. In addition, in an analysis of site preparation effects, Mojeremane et al. (2012) found that types of soil disturbance clearly affected emissions during the first years after mounding on a peaty gley soil. They found that N_2O emissions were lower from mounds and hollows than from an undisturbed soil surface, while CH_4 emissions were highest from hollows, intermediate from undisturbed soil-surface and lowest from the mounds. In another study on three upland soils in Germany, Teepe et al. (2004) observed up to 40 times higher N_2O emissions from compacted soil in wheel ruts than from undisturbed soil, accompanied by significant reductions in CH_4 consumption (or even releases).

The aim of this study was to determine the effects of soil disturbance caused by stump harvesting and site preparation on N_2O and CH_4 emissions during the 2-yr-period following the treatments. We hypothesized that the soil mixing through aeration and destruction of fungal networks would increase the availability of ammonium and nitrate in the soil which, in turn, would increase the magnitude of N_2O fluxes. We also hypothesized that soil disturbances causing wet conditions, such as wheel rutting, would promote CH_4 emissions.

2. Materials and methods

2.1 Study sites

The study was performed at three sites in central Sweden, a subset of 14 experimental sites of stump removal and site preparation established in clear-cuts across the country in 2012–2013. Forest floor C-to-N ratio is a good indicator of nitrogen availability (Gundersen et al., 1998). Since available nitrogen is required for N_2O emissions, the main criterion for selecting the three focal sites was high fertility with C-to-N ratio in mineral soil ranging from 14 to 20 (Table 1). The sites are located in the southern boreal or