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Short-term impacts of soil preparation on greenhouse gas fluxes: A case study in nutrient-poor, clearcut peatland forest

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ABSTRACT

Soil preparation to expedite stand establishment after clearcutting is an extensively applied measure in peatland forest regeneration sites particularly in Fennoscandinavia. Thus far, the impact of preparing peat soil on greenhouse gas fluxes is a chapter unwritten in GHG research on forestry-drained peatlands. Not only is such information vital in order to accurately estimate the GHG balance nationally, it may dictate the very methods used to regenerate forests on peat soils in the future. Over a 22-month period, we studied the impacts of mounding and scalping relative to the control on soil CO_2 (heterotrophic peat soil respiration, SR_p), CH_4, and N_2O fluxes along a moisture gradient in a nutrient-poor, clearcut forestry-drained peatland. First, we measured instantaneous gas fluxes ($g\,m^{-2}\,h^{-1}$) of the microsite types (unprepared, mound, pit, scalp) within a given treatment plot (control, mounding, scalping) in order to estimate their annual rates ($g\,m^{-2}\,a^{-1}$). Then, we estimated annual flux rates for each treatment comprehensively by considering the surface area-based distribution of microsite types in the corresponding treatment plot, and finally, the overall climatic impact of GHG emissions expressed in terms of CO_2 equivalents (100-year GWP) 2–3 years after clearcutting and soil preparation. Compared to the control microsites, instantaneous CO_2 emissions from scalps and pits were lower while those from mounds equivalent. However, increased CO_2 emissions from the unprepared microsites within prepared plots were observed in respect to those of the control. Comprehensively, the annual CO_2 emission rates differed little between treatments, ranging between 929 and 1078 $g\,m^{-2}\,a^{-1}$. Hence, neither mounding nor scalping accelerated annual SR_p relative to the control treatment. Annual fluxes of CH_4 were dependent on the position of the water table. In our wet block, the mounding treatment led to the greatest annual CH_4 emissions (3.62 $g\,m^{-2}\,a^{-1}$), followed by the control (2.14 $g\,m^{-2}\,a^{-1}$) and scalping (1.05 $g\,m^{-2}\,a^{-1}$); in the dry block, however, only the scalping treatment was a net, though minimal, source of CH_4 (0.80 $g\,m^{-2}\,a^{-1}$) while the other two treatments effectively consumed CH_4 (mounding −0.16 $g\,m^{-2}\,a^{-1}$; control −0.05 $g\,m^{-2}\,a^{-1}$). Though annual N_2O emission levels were low (0.05–0.08 $g\,m^{-2}\,a^{-1}$), both soil preparation treatments increased the flux of N_2O from peat soil compared to the control. When considering the fluxes of all three greenhouse gases, the cumulative impact of soil preparation (mounding or scalping) on the global warming potential of the nutrient-poor, clearcut peatland forest was negligible in respect to the control.

1. Introduction

In this era of increased awareness of the consequences of human activities on the Earth's climate, every economic sector, including peatland forestry, has come under scrutiny. Though studies concerned with the effects of drainage on soil carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) fluxes within boreal peatland forests have gradually accumulated (e.g., Martikainen et al., 1995; Minkkinen et al., 2007; Ojanen et al., 2010; Roulet et al., 1993; Silvola et al., 1996; von Arnold et al., 2005), the implications of commonly applied silvicultural measures such as clearcutting (Huttunen et al., 2003; Mäkiranta et al., 2010; Nieminen, 1998; Saari et al., 2009) and particularly soil preparation have gone largely unnoticed. This despite soil preparation being a widely applied treatment when regenerating forests in Fennoscandinavia.

Although Laiho et al. (2004) demonstrated faster decomposition of both Scots pine needle and fine root litter incubated in moss and surface peat layers, respectively, on undrained rather than drained, forested boreal peatland sites due to drainage-induced moisture

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stress, the effects of harvesting and soil preparation on organic matter (OM) decomposition and quality in peatlands are poorly known (Prescott et al., 2000). In fact, the majority of relevant studies have been restricted to undrained wetland soils or those overlain by a thin peat layer (e.g., Trettin et al., 1992, 1997). Minkkinen et al. (2008) suggested that soil preparation may lead to increased release of CO_2 into the atmosphere by intensifying oxidation and decomposition of the peat substrate. For example, mounding is understood to improve soil aeration and local drainage and create warmer soil temperatures which together could potentially accelerate the OM decomposition process and therefore nutrient mineralization (Londo and Mroz, 2001; Örlander et al., 1990; Sutton, 1993). Recent findings of Mojeremane (2009) and Pearson et al. (2011), however, contradict such a proposed increase in decomposition rate in drained peatlands of maritime and boreal regions, respectively.

Soil temperature and water table level (WTL) have both been identified as primary factors controlling OM decomposition in peat soils (Blodau et al., 2004; Mäkiranta et al., 2009; Silvola et al., 1996). The sensitivity of HSR to either of these, however, varies according to site (Minkkinen et al., 2008). On sufficiently drained sites with a WTL deeper than 30 cm, soil temperature tends to be an overwhelmingly better indicator (Minkkinen et al., 2007) though high spatial variation within and between sites has been observed (Mäkiranta et al., 2008; Minkkinen et al., 2007). When the WTL lies closer to the surface, e.g., in wet pristine sites, however, the opposite is typically true (Blodau et al., 2004; Chimner and Cooper, 2003; Riutta et al., 2007). Notably, silvicultural practices influence the interaction of soil temperature and WTL in determining HSR; despite increasing soil temperature, clearcutting of a drained, pine-dominated peatland forest actually lowered the rate of HSR by raising the WTL, which consequently overrode the positive effect of increasing soil temperature on HSR (Mäkiranta et al., 2010). Site type, i.e., fertility reflects the quality and quantity of substrate available to decomposers and vegetation therefore also influencing HSR. Higher C:N ratios are generally understood to limit organic matter decomposition due to a shortage in available nitrogen and an abundance of recalcitrant material (e.g., lignin). HSR typically increases from nutrient-poor to nutrient-rich peatland sites (Minkkinen et al., 2007; Silvola et al., 1996; von Arnold et al., 2005). Increased soil acidity after drainage has also been shown to constrain decomposition on drained peatlands (Laiho et al., 2004; Laine et al., 1995; Minkkinen et al., 1999).

By lowering the WTL and altering the composition of the plant community, drainage reduces CH_4 emissions from peatlands (Martikainen et al., 1995; von Arnold et al., 2005) from 30% to more than 100% (Nykänen et al., 1998) although the change is smallest in ombrotrophic sites, which generally remain sources indeterminately. However, watering up as a result of clearcutting (Heikurainen and Päivänen, 1970; Marcotte et al., 2008) may once again revive CH_4 production and emission from deep peat soils. One of the few studies relevant for our purposes examined the effects of clearcutting two nutrient-rich, drained peatland sites on CH_4 fluxes but found the changes to be negligible even though the WTL clearly rose, perhaps in part due to the slow re-establishment of methanogenic bacteria in old drainage areas (Huttunen et al., 2003). Similarly, Saari et al. (2009) noted net consumption of CH_4 after clearcutting a well drained peatland site covered by spruce-pine mixed forest.

N_2O emission from peat soils is regulated by aerobic nitrification and anaerobic denitrification processes which again are influenced by site nutrient and oxygen status (Martikainen et al., 1993; Regina et al., 1996). N_2O fluxes are difficult to predict and temporally highly sporadic while being less related to WTL and soil temperature compared to those of CO_2 and CH_4 (Minkkinen et al., 2008). Soil C:N ratio has been intimately linked to seasonal N_2O emissions from peat soils (Klemedtsson et al., 2005). Drained pine bogs normally have ratios higher than 30, thus releasing limited amounts of N_2O. Drainage typically increases N_2O emission only from nutrient-rich peatland sites whose pH encourages nitrate formation (Martikainen et al., 1993; Regina et al., 1996). Felling and consequent input of N from slash may nonetheless enhance N_2O formation even in poorer sites (Mäkiranta et al., 2012). In the aforementioned work of Saari et al. (2009), N_2O fluxes shifted from net consumption to net emission in consecutive years after clearcutting apparently due to changes in the decomposition of logging residues and position of the water table. On nutrient-rich drained peatland sites, Huttunen et al. (2003) noted a potential for increased N_2O emissions after clearfelling at least in the short term but Nieminen et al. (1998), on the other hand, found the gaseous nitrogen emission to be insignificant.

In light of the aforepresented, a need exists for evaluating the GHG response of peatlands used in commercial forestry to silvicultural practices including soil preparation. In doing so, the accuracy of estimations regarding the GHG balance at the national level is improved while the predicted impacts on the atmosphere are better founded. In Finland, for example, such information on which to base nationwide GHG estimates and modeling is not only timely but also critical because nearly 390,000 ha of peatland forests are presently due for regeneration as well as an additional 347,000 ha within the next 5 years (Saarinen, 2011). Furthermore, the forthcoming forest renewal is specifically concentrated in pine-dominated stands. To constrict the gap in our present knowledge, we set out to:

(1) Measure the short-term impacts of soil preparation, i.e., mounding and scalping, on soil GHG (CO_2, CH_4, N_2O) emissions from a nutrient-poor, forestry-drained peatland.
(2) Study the dynamics of GHG fluxes and their environmental drivers in different soil preparation treatments.
(3) Estimate the annual fluxes from different soil preparation treatments.

2. Materials and methods

2.1. Study site and experimental treatments

Our study site was located on a 6 ha riverside peatland in Hyytiälä (61°50′41″N 24°17′19″E), Juupajoki municipality, Central Finland. According to the Finnish classification system, the peatland represents a transitional form between dwarf shrub (Vatkg) and *Vaccinium vitis-idaea* (Ptkg II) drained peatland site types (Vasander and Laine, 2008). The field layer in the northern half of the site is dominated by mire vegetation, mainly cottongrass (*Eriophorum vaginatum* L.), bog bilberry (*Vaccinium uliginosum* L.), dwarf birch (*Betula nana* L.), and wild rosemary (*Rhododendron tomentosum* L.), whereas the southern half consists primarily of forest species like lingonberry (*V. vitis-idaea* L.), blueberry (*Vaccinium myrtillus* L.), and common cow-wheat (*Melampyrum pratense* L.), which are complemented by patches of bog bilberry and wild rosemary. Initially drained in 1915 followed by supplementary ditching in 1986, Scots pine (*Pinus sylvestris* L.) forest (155 m^3 ha^{-1}) dominated the peatland prior to clearcutting in the winter 2006. The experimental area was composed of two approximately 0.3 ha blocks based on their apparent differences in moisture regime as evidenced by greater soil sogginess, sensitivity to flooding, and prevalence of mire as opposed to forest vegetation in the Northend vs. the Southend. Mechanical soil preparation (scalping and mounding) and control treatments were randomly assigned to three approximately 30×30 m plots within each block. Thus, the two blocks represented replicates of the three treatments. Both scalping and mounding were done with an excavator in the autumn subsequent