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Changes in biogeochemistry and carbon fluxes in a boreal forest after the clear-cutting and partial burning of slash

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ABSTRACT

We quantified the changes in the soil properties and fluxes of soil CO_2, CH_4 and volatile organic compound (VOC) fluxes following a clear-cut (CC) and prescribed burning of slash (BCC) over a three year time period in a mature spruce forest. Clear-cutting increased soil moisture, soil temperature, pH as well as NH_4–N and NO_3–N concentrations in the soil. PH and soil temperature in the BCC site were even higher than in the CC site.

Probably due to decreased tree root respiration, the soil CO_2 efflux decreased only slightly in the first growing season following the clear-cut. During the following two years, the CO_2 efflux at the CC site was significantly higher than in the mature control forest due to increased decomposition, which was stimulated by higher soil moisture and temperature. The temperature dependencies of the CO_2 efflux did not differ between these sites. The clear-cut and burning of slash, however, decreased the CO_2 efflux and its temperature response in BCC for two years but in the third year, the differences between control and BCC were no longer significant.

Soil was a sink for CH_4 in all treatments. After the clear-cutting and burning of slash, the net CH_4 uptake was immediately decreased, but one year later the uptake was comparable to that of the mature control forest. The CC treatment decreased the soil CH_4 uptake, however, it did not significantly differ from that of the control.

The soil VOC emissions measured at the BCC site were 100-fold compared to those measured before clear-cutting, but the emissions decreased rapidly during the three months following the burning.

Although the CO_2 effluxes from the BCC site were lower for more than 2.5 years compared to the CC site, the total amount of carbon released from prescribed burning was higher due to the immediate carbon losses. Moreover, the clear-cut and burning of slash temporarily decreased the ability of the forest to bind atmospheric CH_4 and increased the VOC emissions significantly.

1. Introduction

Boreal forests soil stores a large proportion of the world's terrestrial carbon (Dixon et al., 1994; Gorham, 1991; Jobbagy and Jackson, 2000). This is due to slow decomposition rates of organic matter under conditions of low litter quality, cold temperatures and anaerobic conditions that result from water logging. Wildfire is an important natural disturbance that occurs in these forests, 1.1–1.5% of which burn each year (Gromtsev, 2002; Hytteborn et al., 2005). Burning releases a pulse of carbon (C) and nitrogen (N) into the atmosphere, the loss depending on the intensity of the fire (Certini, 2005; Homann et al., 2011; Johnson and Curtis, 2001; Rocha and Shaver, 2011). Low-temperature fires may cause a small initial loss of soil C and N, but they may result in later gains due to the

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incorporation of unburnt residues and N-fixing by vegetation (Makoto et al., 2011; Johnson and Curtis, 2001; Jorgense and Wells, 1971). In addition to the direct emissions, fire affects the ecosystem C and N balance over more protracted periods of time by affecting the ecological controls of the C and N cycles as well as the structure and the net primary productivity of the postfire forest. Fires and the ability to recover from them have an important influence in regional C storage in ecosystems, because the C lost by fires is often a significant component in regional C budgets.

In Fennoscandia, wildfires are rare due to effective fire protection that has taken place since the 1900s, and which has possibly increased the amount of soil organic matter in the humus layer in the long run (Wardle et al., 1997). A thick humus layer serves as a stock of C but it also can result in inefficient germination of seeds and seedling establishment and consequently poor forest regeneration. Therefore, prescribed burning of logging residues is sometimes used to facilitate the seedling establishment. The burning is a strong treatment affecting the soil surface layers and exposing mineral soil so that the soil moisture conditions are favourable for seedling germination but it also releases important nutrients in the soil and reduces the competition of ground vegetation. In practice, prescribed burning after logging involves the burning of debris that has been piled (pile burning), wind thrown (wind throw burning), or spread relatively freely over the entire area (broadcast burning) as in this study.

Clear-cuts leave a large amount of litter (as foliage, branches etc.) on the site, but reduce future litter inputs for some time as the primary production of the ecosystem is usually reduced. In addition, clear-cutting reduces root exudates that are rapidly decomposing organic substances leaching out of the roots and used as a substrate for root associated mycorrhiza and bacteria (Pumpanen et al., 2009; Högberg et al., 2001). After the clear-cut and removal of forest canopy, soil becomes exposed to higher insolation, which increases soil temperature during the snow-free period. This effect is even greater on the burnt surface due to the lack of ground vegetation which buffers the temperature variation. Also the colour of the soil surface becomes darker which decreases the albedo compared to clear-cut site (Certini, 2005; O'Halloran et al., 2012). Besides the elimination of ground vegetation, burning influences also many other well-known physical, chemical and biological soil properties affecting soil carbon dioxide (CO_2) effluxes e.g. the quantity and quality of organic matter (Certini, 2005), the availability of nutrients (Covington and Sackett, 1992; Grady and Hart, 2006; Johnson et al., 2007), pH (Certini, 2005), moisture (Ryu et al., 2009; Takakai et al., 2008; Yoshikawa et al., 2002), microbial biomass (Grady and Hart, 2006; Pietikäinen and Fritze, 1995; Sullivan et al., 2011) and microbial species composition (Malmstrom et al., 2009). Due to altered C input and increased soil moisture and temperature, we assume that clear-cutting and leaving the logging slash on the site increases, but the prescribed burning of slash decreases the CO_2 emissions during the first years after the treatments. Nevertheless, we hypothesize (H1) that the sum of carbon lost from the burnt area during and the first years after the treatment exceeds the increased emissions from the clear cut only since the burning strongly decreases the soil carbon storages (Johnson and Curtis, 2001).

The soil CH_4 flux is a sum of CH_4 production by methanogenic microbes and CH_4 uptake by *methanotrophic bacteria in the soil.* In general, boreal forest soils can act as a sink for atmospheric CH_4, and also as a source for CH_4 produced in deeper soil layers (Savage et al., 1997; Saari et al., 2004; Dutaur and Verchot, 2007). Burning (1) decreases the thickness of the organic layer on top of the mineral soil thus enhancing the diffusion of CH_4 and O_2 into the mineral soil, (2) increases soil temperature and thus microbial activity in the soil, which facilitates CH_4 oxidation, and (3) increases the mineral N contents in the soil (Marion et al., 1991). The removal of vegetation by clear-cutting will decrease transpiration, which will increase the soil moisture and thus decrease the diffusivity of gases into the soil. The increased soil moisture may also cause a proliferation of anaerobic regions that may act as a CH_4 source. Thus, we hypothesize that (H2) the clear-cut and prescribed burning of slash increase soil moisture and therefore decrease the overall CH_4 sink.

Forest soils are important sources for volatile organic carbon to air (Aaltonen et al., 2011, 2013). The processes related to their natural production in soils and release into the atmosphere are generally poorly understood. However, decomposition processes, roots and microbes are known to produce these compounds (Asensio et al., 2008; Leff and Fierer, 2008). In boreal forest soils, volatile organic compound (VOC) fluxes have clear seasonal variation the emissions being highest in the spring and in the autumn (Aaltonen et al., 2011, 2013; Hellen et al., 2006). Although the processes behind the seasonality are not fully quantified, at least soil temperature and moisture conditions are connected with many physical and biological processes of soil VOC formation (Aaltonen et al., 2013; Asensio et al., 2008; Leff and Fierer, 2008). Thus, we hypothesize that (H3) clear-cut and prescribed burning of slash increase VOC emissions.

Forest management practices have the potential to change the dynamics of C exchange. Successional patterns and the effect of prescribed burning on soil C stocks are well studied, but the consequences of prescribed burning and natural forest fires on the gaseous C fluxes following burning of slash are largely unknown. Climate change will increase the frequency of wildfires in boreal forests in the future (Bond-Lamberty et al., 2006, 2007), which may further impact upon C exchange dynamics in boreal forests (Flannigan et al., 1998).

The aim of this study was to quantify the changes in the soil properties and fluxes of CO_2, CH_4 and VOCs following the clear-cut and the subsequent prescribed burning of slash in a boreal forest and to study how the treatments change the environmental controls of CO_2 effluxes. For this purpose, we measured soil temperature and moisture continuously. Soil pH, soil carbon and nitrogen, the concentrations of extractable, NH_4^+–N, NO_3^-–N, and the CO_2, CH_4 and VOC fluxes were measured at regular intervals over four consecutive years before and after clear-cutting and after partial burning of slash. The measurements were part of a case study comparing three adjacent, initially similar Norway spruce dominated stands viz: (1) an intact mature spruce forest (control), (2) a clear-cut spruce forest (CC), and (3) a clear-cut and burnt spruce forest (BCC).

2. Methods

2.1. Site and treatments

The experimental site was a 100-year-old Norway spruce (*Picea abies* (L.) H. Karst.) forest which was grown at a distance of 300 m from the research station SMEARII (Hari and Kulmala, 2005) in southern Finland (61°52′ N, 24°17′ E). During the experiment, the weather was constantly monitored at the SMEARII station. Finnish Meteorological Institute records show that the mean annual temperature is +3.5 °C and precipitation is 711 mm in the area (Pirinen et al., 2012). February is the coldest month (mean −7.7 °C) and July the warmest (mean +16.0 °C). The rainiest months are July (92 mm) and August (85 mm).

The area of the studied site was approx. 4.5 ha. The site was classified as the mesic Myrtillus site type (MT) according to the Finnish forest site Classification system (Cajander, 1926) with sparse occurrences of peat. The parent material of the soil is glacial till. In July 2008, we measured the tree stand with 13 relascope sample plots from which the species and the diameters at breast height were recorded for each tree. The diameters at the height of 6.0 m, the