Journal of Environmental Management 228 (2018) 405–415

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Changes in fluxes of carbon dioxide and methane caused by fire in Siberian boreal forest with continuous permafrost

Egle Köster[a,*], Kajar Köster[a], Frank Berninger[a], Anatoly Prokushkin[b], Heidi Aaltonen[a], Xuan Zhou[a], Jukka Pumpanen[c]

[a] Department of Forest Sciences, University of Helsinki, P.O. Box 27, FI-00014 Helsinki, Finland
[b] V. N. Sukachev Institute of Forest of the Siberian Branch of the Russian Academy of Sciences, Russian Federation
[c] Department of Environmental and Biological Sciences, University of Eastern Finland, P.O. Box 1627, FI-70211 Kuopio, Finland

ARTICLE INFO

Keywords:
Greenhouse gas flux
Forest fire
Boreal forest
Permafrost soil
Carbon dioxide
Methane

ABSTRACT

Rising air temperatures and changes in precipitation patterns in boreal ecosystems are changing the fire occurrence regimes (intervals, severity, intensity, etc.). The main impacts of fires are reported to be changes in soil physical and chemical characteristics, vegetation stress, degradation of permafrost, and increased depth of the active layer. Changes in these characteristics influence the dynamics of carbon dioxide (CO_2) and methane (CH_4) fluxes. We have studied the changes in CO_2 and CH_4 fluxes from the soil in boreal forest areas in central Siberia underlain by continuous permafrost and the possible impacts of the aforementioned environmental factors on the emissions of these greenhouse gases. We have used a fire chronosequence of areas, with the last fire occurring 1, 23, 56, and more than 100 years ago. The soils in our study acted as a source of CO_2. Emissions of CO_2 were lowest at the most recently burned area and increased with forest age throughout the fire chronosequence. The CO_2 flux was influenced by the pH of the top 5 cm of the soil, the biomass of the birch (*Betula*) and alder (*Duschekia*) trees, and by the biomass of vascular plants in the ground vegetation. Soils were found to be a CH_4 sink in all our study areas. The uptake of CH_4 was highest in the most recently burned area (forest fire one year ago) and the lowest in the area burned 56 years ago, but the difference between fire chronosequence areas was not significant. According to the linear mixed effect model, none of the tested factors explained the CH_4 flux. The results confirm that the impact of a forest fire on CO_2 flux is long-lasting in Siberian boreal forests, continuing for more than 50 years, but the impact of forest fire on CH_4 flux is minimal.

1. Introduction

Approximately one third of the world's forest area is covered by boreal forests (Kim and Tanaka, 2003). These forests contain about 66% of the world's forest soil carbon (C) pools; thus, this biome type has an important role in the global C balance (Kasischke and Stocks, 2000). Russian forests comprise about 70% of the world's boreal forests and thus their role in the global C cycle cannot be underestimated (Alexeyev et al., 1995; Kasischke and Stocks, 2000). There are more than 520 million ha of boreal forests in the Russian Federation, containing in total about 119 Pg C, of which about 75% is stored in soils and forest floor material (Alexeyev et al., 1995; Kasischke and Stocks, 2000).

The boreal forest zone widely overlaps with the area of continuous permafrost (Brown et al., 1997). In the Russian Federation more than 60% of the terrestrial surface is occupied by permafrost regions (Anisimov and Reneva, 2006). The permafrost in boreal regions is very close to thawing, and the surface organic layer is the most important factor controlling the thickness of the active layer on the permafrost base (Viereck, 1982; Yoshikawa et al., 2003). Generally these high latitude ecosystems are C sinks, absorbing atmospheric carbon dioxide (CO_2) through photosynthesis and releasing it slowly from decomposing organic matter (Fan et al., 1998), but even small changes in these large ecosystems may evoke significant changes in the greenhouse gas (GHG) balance of the atmosphere. The occurrence of permafrost makes these ecosystems even more vulnerable to possible disturbances and changing climate (Kim and Tanaka, 2003; Zona, 2016). Increases in the depth of the seasonally thawed active layer may increase soil temperature, and with it decomposition (Grosse et al., 2011). The accompanying decrease in soil moisture is another factor that increases the decomposition rates (Zona, 2016). Increased decomposition in turn leads to elevated GHG emissions in the form of CO_2 and/or methane (CH_4) (Zona, 2016).

Fire is a critical disturbance in boreal forests, and every year large

* Corresponding author.
E-mail address: egle.koster@helsinki.fi (E. Köster).

https://doi.org/10.1016/j.jenvman.2018.09.051
Received 31 May 2018; Received in revised form 10 September 2018; Accepted 14 September 2018

areas are burned (Kim and Tanaka, 2003; Flannigan et al., 2009). It is estimated that about 5–20 million ha of forests burn annually in the boreal biome (Kasischke and Stocks, 2000; Flannigan et al., 2009; Global Forest Atlas), the majority of which (according to some estimates even about 12 million ha) is in the Russian Federation (Ponomarev et al., 2016). Although human activities are considered to be responsible for about 80–90% of forest fires in the Russian Federation (Karpachevskiy, 2004), in remote areas fire occurrence is driven by nature (Ganteaume et al., 2013). In Siberia, larch (*Larix* sp.) dominates the forest communities, with specific characteristics such as low crown closure and dense ground cover. Although fires in these areas are mostly ground fires, a shallow root zone caused by permafrost is irreversibly damaged in the fire, and so fires in these forests are mostly stand-replacing (Ponomarev et al., 2016). In the areas with a permafrost base, severe wildfires accelerate the degradation of permafrost, and this in turn influences the further succession of the areas (Taş et al., 2014) as well as the C balance of these ecosystems (Kasischke et al., 1995; Takakai et al., 2008). Furthermore, it is suggested that due to climate change the severity of forest fires is going to increase by up to 50% by the middle of the current century (Flannigan et al., 2000). Predicted shorter fire return intervals and increased fire severity leads to younger stands and decreased C storage (Kasischke et al., 1995).

It has been observed that fires strongly influence the soil C dynamics and thus have an important impact also on GHG fluxes and emission rates (Sullivan et al., 2011; Köster et al., 2017). The release of CO_2 and other GHGs into the atmosphere during the combustion process is a primary effect of fire (Nakano, 2006; Urbanski et al., 2009; Sullivan et al., 2011). Fire changes soil physical and chemical properties, respiration and decomposition processes, and soil moisture balance, and these in turn affect the soil GHG fluxes for a long period of time after the fire (Zavala et al., 2014; Köster et al., 2015, 2017). Several studies have referred to the fact that the heat from the fire event does not significantly affect the active layer (Dyrness, 1982; Viereck, 1982; Brown, 1983; Yoshikawa et al., 2003). However, in the permafrost areas the effect of fire is extended, as combustion removes the insulating organic layer and causes a decrease in surface albedo during the summer, allowing the permafrost to thaw (Yoshikawa et al., 2003). Furthermore, due to slow regeneration of vegetation in the boreal permafrost areas, rising soil temperatures may increase the metabolic rates of decomposing microbes in the longer term (Jorgenson et al., 2010). The depth of the active layer has been found to increase for approximately 3–5 years after the forest fire (Dyrness, 1982; Viereck, 1982; Brown, 1983; Yoshikawa et al., 2003) due to decreased soil moisture and increased soil temperatures (Kwon et al., 2016; Zona, 2016). Recovering vegetation allows soils to cool down, and the depth of the active layer starts to reduce (Fisher et al., 2016). Thus, these changes may directly influence the fluxes of CO_2 and CH_4 between the soil and the atmosphere (Kasischke et al., 1995; Kim and Tanaka, 2003; Kim, 2013).

CO_2 emissions from the soil originate from the decomposition of soil organic matter and plant root respiration, and are the major component of the global terrestrial C cycle (Takakai et al., 2008). Forest fires directly influence ecosystem C dynamics and CO_2 flux. During the fire, a pulse of CO_2 and CH_4 from the combustion process is released into the atmosphere (Nakano, 2006; Sullivan et al., 2011; Taş et al., 2014). However, post-fire soils have the potential to release more CO_2 and CH_4 to the atmosphere due to changed soil moisture conditions and elevated temperatures (Ullah and Moore, 2011). It has been observed that after the fire, the decomposition of fire-produced necromass releases about three times more CO_2 from the soil (Burke et al., 1997). In permafrost areas, the degradation of permafrost and deepening of the active layer promotes the release of C stored in the frozen soil (Zona, 2016), which elevates further the impact of fire on the chemical composition of the atmosphere and the Earth's climate system (Urbanski et al., 2009).

Non-paludified boreal forests usually act as sinks of CH_4 (Kulmala et al., 2014; Köster et al., 2015). It has been observed that in boreal forests, fire increases the uptake of CH_4 (Takakai et al., 2008; Kulmala et al., 2014; Taş et al., 2014; Morishita et al., 2015), and site-specific environmental conditions (soil hydrology, vegetation, soil biota, available soil organic C etc.) are the main drivers of the post-fire changes in CH_4 fluxes (Nakano, 2006; Sullivan et al., 2011). In southern boreal forests, the uptake of CH_4 increases after the fire, returning to initial unburned conditions after one year (Kulmala et al., 2014; Taş et al., 2014). It is suggested that the main reason for this is the fast recovery of the microbial community (Kulmala et al., 2014). In northern boreal forest with a permafrost base, the influence of fire on the CH_4 flux should last longer, as the post-fire induced thawing of the permafrost influences the soil temperatures and soil hydrological conditions for a relatively long period of time (Yoshikawa et al., 2003; Zona, 2016).

Although the effect of fire on permafrost forest areas has evoked the interest of scientists for a long time, the long-term (decadal) changes in the fluxes of different GHGs caused by forest fires have received less attention as most studies concentrate on the short-term (time scale of a few years) changes (Takakai et al., 2008; Morishita et al., 2015; Song et al., 2018). In this study, we investigated a long-term chronosequence of forest fires in boreal deciduous coniferous forests with a permafrost base in the central part of Siberia, the Russian Federation. Areas that had differing time periods since the last forest fire, but with comparable ecological conditions, were chosen for testing the long-term impact of fire on CO_2 and CH_4 fluxes. We compared the role of factors such as time since fire, soil temperature, soil moisture, depth of the active layer, living and dead tree biomass, and ground vegetation biomass (grasses and mosses), and estimated how these factors influence the GHG fluxes across a fire chronosequence. Our key research question was: How does time since the last forest fire influence the soil CO_2 and CH_4 fluxes in permafrost areas? Our hypotheses were: a) the fluxes of CO_2 and CH_4 will change as a consequence of fire and associated permafrost thawing, and the magnitude of the changes correlates with the time since the last fire; b) the fluxes of CO_2 and CH_4 are positively correlated with the depth of the active layer on top of the permafrost during the vegetation period; and c) the recovery of the CO_2 and CH_4 fluxes to the pre-fire levels is related to the recovery of the vegetation.

2. Methods

2.1. Study area

An intensive measurement campaign was conducted in July 2016, close to Tura (Evenkiysky district of Krasnoyarsk kray, the Russian Federation) (64°16′ N, 100°13′ E) in the northern part of the Central Siberian Plateau. The study sites are located within the basin of the Nizhnyaya Tunguska River and its tributary, the Kochechum River, both belonging to the Yenisei River watershed (Fig. 1).

The study area has continuous permafrost (Osawa and Zyryanova, 2010) and a cold continental climate. The average temperature in January (the coldest month) is −36 °C, and in July (the warmest month) 16 °C (Prokushkin et al., 2006). The average annual temperature is −9.5 °C (Startsev et al., 2017). Average annual precipitation for the region is 250–390 mm (Prokushkin et al., 2006; Kharuk et al., 2011), about 30–40% of which falls as snow, which commonly covers the ground for about 219–235 days a year (Prokushkin et al., 2006). Average summer precipitation is about 180 mm (Kharuk et al., 2011).

Soils of the area are characterized by a large proportion of gravel, shallow (20–40 cm) depths, and low or medium clay contents of fine earth (Prokushkin et al., 2006). Based on the soil geographic division of the Russian Federation, soils in the area belong to the central Siberian province of permafrost-affected taiga soils, with a predominance of cryozems with shallow permafrost (Startsev et al., 2017). According to the IUSS Working Group, the soils in the area are classified as gelisols (IUSS Working Group WRB, 2006). Soils of the area have slightly acidic pH.