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Low-intensity surface fire effects on carbon and nitrogen cycling in soil and soil solution of a Scots pine forest in central Germany

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ABSTRACT

Dissolved and particulate organic carbon (DOC, POC) and nitrogen (DN, PN) are important constituents and indicators of the C and N dynamics in forested ecosystems, but little is known about fire effects on the fluxes of these elements. Biweekly fluxes at three different soil depths (organic layer O, mineral soil A, mineral soil B) were measured with zero-tension lysimeters before and after (prescribed) low-intensity surface fires in a Scots pine forest in central Germany. Measurements of soil organic C and total N concentrations, cold (soluble) and hot (labile) water-extractable DOC and DN, and soil respiration also were conducted for both pre- and post-burn bulk soils. Linear mixed-effect modelling (LMM) revealed that repeated low-intensity fire reduced DOC (− 64%) and DN (− 11%) fluxes in the organic layer, but increased soil CO_2 fluxes (+ 7%). A nutrient flush from the charred material into the A horizon, as indicated by an enhanced solution pH (+ 11%) and electrical conductivity (+ 68%), may have stimulated microbial activity, leading to enhanced DOC (+ 47%) and DN (+ 202%) production and fluxes, respectively. The B horizon was unaffected by the fire treatment and retained DOC and DN. In contrast to DOC and DN fluxes, POC and PN fluxes were less affected by the fire treatment and decoupled from those of dissolved organic matter (DOM). Our findings indicate that low-intensity surface fires can significantly affect generally nutrient-poor soil systems by causing a short-term flush ("hot moment") of DOM in the mineral A horizon (vertical "hot spot") and by sorption in the mineral B horizon.

1. Introduction

Fire represents a natural disturbance in forest ecosystems (Pickett and White, 1985) affecting physical and chemical properties of soils that are central for ecosystem functioning. Fires, for instance, have been documented to alter infiltration rates and degree of hydrophobicity (DeBano, 1981), bulk density (Andreu et al., 2001), soil pH and electrical conductivity (EC) (Alauzis et al., 2004), as well as soil carbon (C), nitrogen (N), and other nutrient pools (Baird et al., 1999; Certini, 2005; Fernández et al., 1997; Nave et al., 2011). The order of magnitude of alterations in soil properties depends on the spatial distribution of fuel and soil organic matter (SOM) (Prieto-Fernández et al., 2004; Williams et al., 2012) as well as the fire intensity (Johnson, 1992; Schoch and Binkley, 1986). Fire can have short-term, long-term or permanent consequences for the forest soil and the forest ecosystem, respectively (Certini, 2005; Kutiel and Naveh, 1987; Neary et al., 1999). However, how these patterns vary with depth is less known.

The forest floor and the upper centimeters of the mineral soil, where most of the SOM and nutrients are stored (Batjes, 1996; Meiwes et al., 2002), are most prone to the influences of fire (DeBano and Conrad, 1978; Wan et al., 2001). Fire acts as an immediate mineralizing and mobilizing agent (McKee, 1982; St. John and Rundel, 1976), leading to altered release rates of C via soil and microbial respiration (Holden and Treseder, 2013; Tufekcioglu et al., 2010) and leaching of elements (Michalzik and Martin, 2013; Murphy et al., 2006b).

Much attention has been paid on fire-related leaching losses of anions and cations using absorbing resins (Johnson et al., 2007; Murphy et al., 2006a, 2006b), but this method does not permit the determination of dissolved organic carbon (DOC) and dissolved total nitrogen (DN) or high temporal resolution of C and N fluxes. Accordingly, relatively few studies have monitored the water-flux driven release of dissolved organic matter (DOM) and elements from fire-affected forest floor and mineral soil in the short- or longer-term (Boerner and Forman, 1982; Chorover et al., 1994; Clay et al., 2009; Michalzik and Martin,

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Abbreviations: A, upper mineral soil horizon; B, lower mineral soil horizon; BP, bulk precipitation; C_{org}, organic carbon; CT, control; DN, dissolved nitrogen; DOC, dissolved organic carbon; DOC_{cold} and DN_{cold}, DOC and DN concentration in cold water-extracts; DOC_{hot} and DN_{hot}, DOC and DN concentration in hot water-extracts; DOM, dissolved organic matter; FF, forest floor; FM, fire-manipulated; LMM, Linear mixed-effect model; N_t, total nitrogen; O, organic layer; TF, throughfall; TraLay, transitional layer

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2013; Pilkington et al., 2007; Potthast et al., 2017; Shibata et al., 2003). Responses to fire are highly variable with space and time and can cause enhanced reaction rates (McClain et al., 2003). Because DOC is a crucial component of the global C cycle (Schulze et al., 2009), it is important to understand fire-related changes in DOC to improve the evaluation of fire impacts on the C cycle in the short- and longer term. Likewise, it is essential to understand nitrogen dynamics following a fire since N is a limiting factor for plant growth (Ellenberg, 1977) and immediately responds to fire since it volatilized at relatively low temperatures beginning at 200 °C (Knight, 1966; White et al., 1973).

Particulate organic carbon and nitrogen (POC and PN, particle size ranging from 0.45 µm to 2 mm) also contribute significantly to the C– and N-cycles in forest ecosystems. However, only a few studies include these fractions in budget calculations (le Mellec et al., 2010; Michalzik et al., 2016; Shibata et al., 2001). In addition, fire-induced effects on water-extractable cations (e.g., Ca^{2+}, Mg^{2+}) and other elements (total sulfur and phosphorous) has been studied by Pereira and Úbeda (2010) and Pereira et al. (2012, 2014), but little is known about the fire-related changes in water-extractable DOC (Shibata et al., 2003). We know of no study investigating fire effects on cold and hot water-extractable DOC and DN. Cold water-extracts indicate readily soluble C and N, and hot water-extracts represent labile and biological reactive C and N (Burford and Bremner, 1975; Ghani et al., 2003; Gregorich et al., 2003; McGill et al., 1986). The soluble as well as the labile C can be used as an indicator for the release potential of DOM and biotic processes (e.g. microbial activity and soil respiration, respectively). Large amounts of labile C may enhance the microbial activity and respiration (Holden and Treseder, 2013), respectively, as demonstrated by strong correlations to microbial biomass C and soil respiration rates (Fischer, 1993; Sparling et al., 1998). Although fire-affected CO_2 soil respiration rates have been widely studied in laboratory and field (monitoring) studies (Bauhus et al., 1993; Fritze et al., 1993; Singh et al., 2008; Weber, 1990), little is known about the interplay among soil respiration, water-extractable DOM, and DOM fluxes in the course of low-intensity fire events.

Forest fires have occasionally occurred in Germany, especially in the eastern part (Lasch-Born et al., 2015), where *Pinus* stands on sandy or sandy-loamy soils dominate (Thonicke and Cramer, 2006). The federal state of Thuringia is covered by about 550,000 ha of forest, which consists of 62% coniferous trees (ThüringenForst, 2013). In Thuringia, the number of forest fires per annum ranged between 10 and 90 with the area burned between 0.3 and 18.4 ha (ThüringenForst, pers. comm.). Most forest fires in Thuringia were caused by the European heat wave in 2003. It is predicted that climate change will increase the occurrence of fire-prone weather conditions in Germany with decreased summer precipitation and increased air temperatures (UBA, 2007), which, in turn, is expected to increase the frequency of fires.

In this paper, we reveal the effects of fire on C and N dynamics in a *Pinus*-dominated forest stand in central Germany (Thuringia). We used 2-years monitoring data of DOC and DN fluxes, POC and PN fluxes, soil respiration rates, as well as cold and hot water-extractable DOC and DN to answer some central questions about C and N cycling after a low-intensity fire. The central questions of this study were:

(1) Do low-intensity surface fires affect the fluxes of dissolved and particulate organic C and total N in leachates of the organic layer and mineral soil horizons? Are DOM and POM fluxes coupled and follow the same temporal pattern after a fire treatment? How are the fire-affected leachates of the different soil layers (O, A, B) connected?

(2) Do low-intensity surface fires induce short- (< 3 months) or medium-term (8 months) effects on C and N fluxes?

(3) Are the fire-affected water-extractable soluble and labile C and N fractions linked with the post-fire dynamics of dissolved and particulate organic C and N, and do these fractions act as a proxy for the subsequent C and N dynamics in the field?

(4) Is the soil respiration rate affected by the low-intensity surface fire and how is it linked to changes in OM cycling?

As such, this study will advance the scientific literature by providing insights into the fire-induced alterations in leachates from three different soil depths as well as temporal dynamics and fluxes of dissolved and particulate C and N. Consequently, the present study provides a base for the impact assessment of low-intensity surface fires that are expected to increase in frequency as a result of climate change (UBA, 2007), thereby providing new perspectives on the role of fire in ecosystem functioning.

2. Materials and methods

2.1. Site description and experimental set-up

The study area (50° 47′ 51 N, 11° 41′ 35 E) is located in a pine forest in the valley "Rothehofsmühle", which is situated approximately 20 km southeast of Jena in Thuringia, central Germany. A small creek ("Zippenbach") forms part of the catchment runoff of this valley. The study area is embedded in a hilly landscape at an altitude between 170 and 450 m a.s.l. and encompasses various slope levels ranging from moderate (10°) to steep (> 30°) slopes. Thirty-year mean annual precipitation is 720 mm and mean annual air temperature is 8.4 °C (ThüringenForst, 2013). The prevailing wind direction is west to southwest. However, frequent easterly winds occurring between February and May, in combination with low rain amounts and low humidity, can sometimes trigger spring droughts (Kunze, 2000). Together with the plant residues of the last growing season these conditions increase the chance for surface fires.

The forest overstory consists primarily of 62–130 year old Scots pine (*Pinus sylvestris* L.) and partly of 20–130 year old Norway spruce (*Picea abies* (L.) H. Karst.). Canopy cover ranges from 50 to 75%. Surface vegetation consists of moss (*Pleurozium schreberi* (Brid.) Mitt., *Hypnum cupressiforme* Hedw. S·Str., *Leucobryum glaucum* (Hedw.) Ångstr., among others), blueberry (*Vaccinium myrtillus* L.), wood fern (*Dryopteris* spec. Adans.) and common wood sorrel (*Oxalis acetosella* L.) as well as younger individuals of pine and spruce derived from natural regeneration.

The soil types are derived from Triassic Sandstone ("Oberer und Mittlerer Buntsandstein") forming a mosaic of Spodosols and dystric to spodic Cambisols, depending on the presence of loess layers (WRB, 2015). The underlying mineral soil is characterized by a slightly leached and humified A horizon (average thickness 8 cm) and a spodic to weathered B horizon (average thickness 20 cm). The soil texture is dominated by silty and sandy loam. The humus forms are classified as moder to raw humus with varying thicknesses (5–16 cm) depending on stand structure and topographic conditions.

The experimental set-up was a paired block design encompassing three spatial site replicates, two located on south-facing slopes and one on a north-facing slope (Fig. 1). Each site consists of a control (CT) and fire manipulated (FM) treatment area (800 m^2). Each treatment area was equipped with throughfall samplers (TF, $n = 2$, with a sampling area of 314 cm^2 each), to monitor the input of elements to the forest floor, and with zero-tension lysimeters ($n = 9$, with a sampling area of 284 cm^2 each) to sample the soil leachates. The lysimeters were installed underneath the organic layer (O), upper mineral horizon (A), and lower mineral horizon (B). The A lysimeters contained the A horizon as well as the O layer, and B lysimeters contained all three horizons. Each zero-tension lysimeter consisted of a polyethylene cylinder (diameter 19 cm), which is closed at the bottom. The lysimeter contains an undisturbed soil monolith, which is placed on a perforated plate in order to allow the soil solution pass through the soil monolith into a storage area (between perforated plate and lysimeter bottom). The stored soil solution could be pumped out via a tube system. The soil monolith was cut out – as undisturbed as possible - with a polyethylene cylinder (diameter 19 cm) and was placed carefully inside the lysimeter. The hole from the soil monolith was used to install the filled lysimeter.