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Land-use and fire drive temporal patterns of soil solution chemistry and nutrient fluxes

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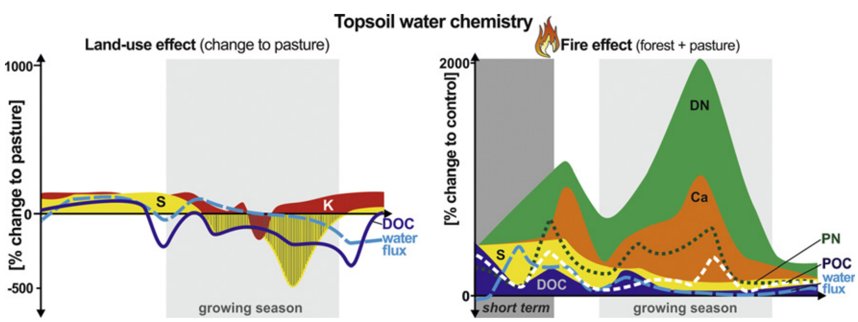
HIGHLIGHTS

- Field study testing the effect of land-use and fire on topsoil water chemistry
- Biweekly tracking of element flux rates in beech forest vs. pasture over 1 yr
- Fire overrides land-use effect on the magnitude and timing of element release
- Fire triggers release of N, S, base cations and particulate OM into the subsurface
- Pasture ecosystems less prone to nutrient losses than forests following fire events

GRAPHICAL ABSTRACT



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ABSTRACT

Land-use type and ecosystem disturbances are important drivers for element cycling and bear the potential to modulate soil processes and hence ecosystem functions. To better understand the effect of such drivers on the magnitude and temporal patterns of organic matter (OM) and associated nutrient fluxes in soils, continuous flux monitoring is indispensable but insufficiently studied yet. We conducted a field study to elucidate the impact of land-use and surface fires on OM and nutrient fluxes with soil solution regarding seasonal and temporal patterns analyzing short (<3 months) and medium-term (3–12 months) effects. Control and prescribed fire-treated topsoil horizons in beech forests and pastures were monitored biweekly for dissolved and particulate OM (DOM, POM) and solution chemistry (pH value, elements: Ca, Mg, Na, K, Al, Fe, Mn, P, S, Si) over one post-fire year. Linear mixed model analyses exhibited that mean annual DOM and POM fluxes did not differ between the two land-use types, but were subjected to strong seasonal patterns. Fire disturbance significantly lowered the annual soil solution pH in both land-uses and increased water fluxes, while DOC fluxes remained unaffected. A positive response of POC and S to fire was limited to short-term effects, while amplified particulate and dissolved nitrogen fluxes were observed in the longer run and co-ocurred with accelerated Ca and Mg fluxes. In summary, surface fires generated stronger effects on element fluxes than the land-use. Fire-induced increases in POM fluxes suggest that the particulate fraction represent a major pathway of OM translocation into the subsoil and beyond. With regard to ecosystem functions, pasture ecosystems were less prone to the risk of nutrient losses following fire events than the forest. In pastures, fire-induced base cation export may accelerate soil acidification, consequently exhausting soil buffer systems and thus may reduce the resilience to acidic depositions and disturbances.
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1. Introduction

Fluxes of elements such as carbon (C), nitrogen (N), and sulfur (S) connect the compartments within and among ecosystems and form central aspects of ecosystem functions (Chapin et al., 2011; Nadrowski et al., 2010). The land-use type and the regime of ecosystem disturbances are known as important drivers for element cycling (Chapin et al., 2011). Besides living organisms, climatic conditions and the physical and chemical soil status are modulating the extent and temporal variations of element fluxes (Bormann and Likens, 1979). Temporal heterogeneity of transport flux rates among elements may cause imbalances in biogeochemical processes and element cycles as well as alterations of the functioning of the respective ecosystems (Bernhardt et al., 2017).

A sensitive indicator to identify impacts of disturbing events on biogeochemical processes is the water-bound organic matter (OM) in soils (Zsolnay, 2003). According to Zsolnay (2003), it represents the integrating link between the biosphere, pedophere, surface and subsurface hydrosphere of the Earth's Critical Zone (Richter and Mobley, 2009). Water-bound OM comprising the dissolved (DOM) and particulate fraction (POM; 0.45 μm < POM < 500 μm), can be translocated/leached from the topsoil to the aquifers or can be redistributed by erosion, and exported to downstream aquatic ecosystems (Boerner, 1982). DOM and POM are the most mobile, biologically relevant and reactive fractions in soils (Kalbitz et al., 2000) responding rapidly to land-use (Bolan et al., 2011) and ecosystem disturbances (Michalzik et al., 2016).

Changes in soil OM stocks, as associated with forest to pasture conversion or different land management strategies, are driven by microclimatic and biogeochemical alterations (e.g. indicated by soil temperature, water content and the pH value). These alterations can relate to e.g., accelerated rates of OM turnover (Potthast et al., 2012) and can lead to increases in volatile (CO_2), particulate, and leaching losses of organic carbon from the soil (Bolan et al., 2011; Lal, 2004). In this context, most studies dealing with effects of land-use change, mainly focused on bulk soil analyses at discrete time points (Schöning et al., 2013; Vesterdal et al., 2011; Wiesmeier et al., 2012), but disregarded element fluxes with soil solution continously monitored over time.

Disturbances by fire can have distinct impacts on soil biogeochemical processes and hence on ecosystem functions depending on the ecosystem, fire-regime, and post-fire climatic conditions. In view of climate change, the frequency and severity of fires are expected to increase as the abundance of extreme weather events, such as droughts, is projected to amplify (Krawchuk et al., 2009). Low-severity fires (surface fires) represent the most commonly occurring fire type in Central European forested ecosystems. Surface fires are characterized by a steep temperature gradient in the soil and temperatures of <300 °C at the soil surface (Franklin et al., 1997). In forested ecosystems, surface fires directly affect the forest floor, where most of the soil OM (SOM) and nutrients are stored (Caldwell et al., 2002; Michalzik et al., 2001) altering the distribution (forest floor vs. mineral soil), binding forms (organic vs. inorganic) (Certini, 2005), and availability (water solubility) of OM and associated nutrients (Beese and Divisch, 1980; Schaller et al., 2015; Unzué-Belmonte et al., 2016).

In contrast to forests, surface fires in pasture ecosystems directly disturb most of the aboveground plant biomass reducing evapotranspiration and the uptake capacity for nutrients until vegetation recovery sets in. Due to increased plant-available nutrients (calcium (Ca), magnesium (Mg), potassium (K)) shortly after low-severity grassland fires, the vegetation is capable to rapidly recover (Pereira et al., 2017). However, the release of mobile forms of elements after a fire might be followed by an accelerated element loss depending on vegetation cover, topography (specific microclimate), pre- and post-climatic conditions, fire-severity (degree of vegetation disturbance, ash composition), and soil type (soil chemical status as indicated by pH value, desorption – sorption properties) (Campos et al., 2016; Certini, 2005; Schaller et al., 2015; Unzué-Belmonte et al., 2016).

Fire-derived variations in ecosystem's OM and nutrient cycling can be short- to long-term (Chorover et al., 1994; Neary et al., 1999) and can interact with seasonal variations in temperature and water input as with extreme weather events (Ginzburg and Steinberger, 2012; Helliwell et al., 2010; Wang et al., 2012). Following fire disturbances, the intensity of transformations (e.g. mineralization) of water-bound OM and translocations of nutrients are at least one order of magnitude higher than under regular conditions (Michalzik and Martin, 2013), and these variations can persist at temporal scales spanning days, months to years (Helliwell et al., 2010; Wang et al., 2012). Substantial work has been performed to test the effects of fire on soil properties (i.e., pH value, microbial activity), SOM, and element stocks (Caldwell et al., 2002; Czimczik et al., 2005; Hockaday et al., 2007; Pereira et al., 2017). However, studies testing the interplay between low-intensity fires and OM and nutrient fluxes with soil solution considering temporal patterns as determined by continuous field monitoring, are scarce (Boerner and Forman, 1982; Michalzik and Martin, 2013).

Consequently, temporally high loss rates of nutrients and OM from soils due to fire may occur at one land-use type but not at another. These deviations may have the potential to produce land-use type specific fingerprints on the subsurface of the Earth's Critical Zone, changing ecosystem functioning and as a result inducing feedback loops to biological processes (i.e., microbial activity, plant biomass production, aquifer biodiversity) (Küsel et al., 2016).

To elucidate land-use specific fire effects on solution chemistry and on OM and nutrient fluxes, the following research hypotheses are addressed: (I) Effect of land-use (forest vs. pasture): We expect to find seasonal dynamics of OM and nutrient fluxes due to time-delayed nutrient release and plant demand (asynchronous patterns of OM mineralization and plant uptake). Differences in flux dynamics are assumed to be related to land-use type specific site/soil conditions and microclimate. (II) Effect of prescribed fire: We hypothesize that soil solution chemistry is differentially impacted by surface fires due to contrasting fire fuel of forest and pasture ecosystems. Furthermore, low-severity fires are assumed to induce a mobilization of DOM, POM, and element fluxes in soil solutions of both land-uses while fire-induced pH increases may vary with land-use type due to different amounts of ash-input. We expect the dominance of short-term pulses (<3 months) to be strong and medium-term (12 months) pulses to be low.

In order to answer these questions, we focus on the comparison of water-bound nutrient and OM fluxes between the topsoils of two characteristic land-use types: natural beech forest and pasture. Furthermore, we aim to elucidate land-use-specific nutrient and OM flux changes after a prescribed surface fire event by biweekly sampling intervals during the first post-fire year in the Hainich region, Central Europe.

2. Materials and methods

2.1. Study area and sites

The study area is located in the Hainich area, West-Thuringia, Central Germany, forming part of the Critical Zone Exploratory (CZE) which was established as an interdisciplinary research platform on subsurface biodiversity within the Collaborative Research Center (CRC) "AquaDiva – Understanding the Links Between Surface and Subsurface Biogeosphere" (Küsel et al., 2016). Apart from arable land-use, forests and pastures represent the most common land-use types in that area. The climate is characterized by a mean annual air temperature of 9.0 °C and a mean annual precipitation of 600 mm (Unstrut valley, Bad Langensalza). The predominant soil type of the study area is classified as Calcaric Cambisol (Siltic) (IUSS Working Group WRB, 2015) developed from carbonate rocks (German Triassic Muschelkalk formations) and aeolian deposits (Pleistocene Loess). For the experimental fire manipulation three spatially independent study sites (site area = 1 ha; 51° 0.6739 N 10° 24.542 E, alt. 360 m a.s.l.) per land-use type (F = forest, P = pasture) were selected. The six sites are located along a topo-

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