

Fire enhances phosphorus availability in topsoils depending on binding properties

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Abstract. Fire can have large effects on ecosystems, with phosphorus being highly important in this regard, especially when considering productivity in burned or adjacent ecosystems after fire. Unfortunately, existing data pose contradictions and methodological challenges to assessing P availability. Here, the impact of fire on topsoil available P was estimated using three different types of organic soil layers (raw humus from spruce, humus from beech, and peat) and two fire regimes (obtaining black carbon and ash). Our findings suggest a strong fire impact on P availability, by enhancing available P during burning to black carbon (~10-fold), and to ash (~2- to 7.5-fold) dependent on calcite content. Fire impact on P availability is on a similar order of magnitude as mineral weathering and annual P cycling/uptake in/by ecosystems. Furthermore, the proportion of available P in relation to total P depends on the origin of the organic soil layers. When related to the remaining mass after burning, as is commonly done, P availability can be overestimated by up to 1400%. Results from this study provide a realistic magnitude of shifts in P release and P availability by fire events of different intensity for widely abundant ecosystem conditions. Taking the importance of P for ecosystem processes into account, these results are highly relevant, because fires for fuel reduction are a common application, and for temperate and boreal ecosystems even moderate climate change scenarios predict an increasing appearance of fires in these regions.

Key words: biogeochemistry; black ash; ecosystem processes; fire impact; fuel reduction; incineration; nutrients; phosphorus availability; plant nutrition; Tharandt Forest, Germany; topsoil.

INTRODUCTION

In the course of global climate change, terrestrial ecosystems are subjected to increasingly longer drought intervals (Nepstad et al. 1999, Richard et al. 2001, Breshears et al. 2005, Xiao et al. 2009). Drought, in turn, enhances the possibility of fire in these ecosystems (Xiao and Zhuang 2007). Simulations show that global climate change could lead to a strong increase of fire probabilities in some regions, but decrease in others (Krawchuk et al. 2009). Consequently, the relevance of fire as a driving force for the structure and functioning of terrestrial ecosystems in many regions may increase due to global change (Kelly et al. 2013). Fires are both natural (independent from humans) and human-set (Bowman et al. 2011), and occur seasonally, depending on latitude and longitude (Carmona-Moreno et al.

2005). Most fires are soil surface fires, impacting not only vegetation but also surficial organic soil layers (Gonzalez-Perez et al. 2004). Different fire intensities (differing in temperature and duration) occur, resulting in a transformation of the initial organic matter to either “black carbon” (BC, formed at ~350°C by smoldering fire) or ash (formed at ~550°C, full oxidation) (Gonzalez-Perez et al. 2004), with possible contrasting effects on nutrient cycling within these systems. The transformation of organic matter to black carbon and ash also depends on soil moisture and organic layer thickness, with a strong decrease of oxygen with increasing organic layer thickness and soil moisture resulting in smoldering fires with a duration of several hours (Gonzalez-Perez et al. 2004, Bento-Goncalves et al. 2012). With this transformation from organic matter to BC or ash, the chemical properties may change, resulting not only in changed nutrient content (e.g., carbon and nitrogen can degas due to burning) (Page et al. 2002, Gonzalez-Perez et al. 2004), but also in altered nutrient availability (e.g., mineralization of organic matter of different intrinsic biodegradability, changes in sorption capacity) (Pereira et al. 2012).

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The relevance for phosphorus (P) in this context is clear, because of its significant impact on biomass production in terrestrial and aquatic ecosystems (Tilman et al. 1986, Elser et al. 2007). The availability of inorganic P in terrestrial ecosystems depends in part on bedrock, state of soil formation, pH, and P-binding soil materials (Marschner 2003). Organic layers of soils are important in this context, because they store high amounts of P. During vegetation development, large amounts of mineral P are relocated from mineral soil to the soil surface via plant litter and are particularly immobilized as organic P (Walker and Syers 1976, Vitousek et al. 2010). Large quantities of plant roots are abundant in close vicinity to these substrates, producing extracellular phosphatases to hydrolyze or mobilize the organic bound P sources. The organic layer is also important for the export of P from forest to aquatic systems (Nixon et al. 1996), where P is important for carbon turnover in phytoplankton (Tilman et al. 1986). However, the impact of fire in relation to these well-documented processes is not entirely clear.

During burning of organic matter, P availability increases significantly (Ewel et al. 1981). The highest P availability was found for BC compared to ash, although differences were limited (Ngoc Nguyen et al. 2014). Yet, the possible P-binding components in ash responsible for this reduction of P availability are not known.

Considering the effects of fire on terrestrial and neighboring aquatic ecosystems via impact on P availability, it is important to assess the impact of fire on terrestrial P availability for different fire treatments (resulting in BC or ash) and different soil organic layer types (from different ecosystems). Most fire studies relate nutrient content to the soil mass after burning, typically being field studies that simply measured the P availability in the remaining material (Humphreys and Lambert 1965, Ewel et al. 1981, Turrion et al. 2010, Pereira et al. 2012, Ngoc Nguyen et al. 2014), not relative to the initial soil mass prior to burning, which can lead to overestimations of P availability and may lead to incorrect conclusions. In order to overcome this lack of knowledge and some existing inconsistencies, we estimated the impact of fire on P availability related to initial soil mass in three different types of organic soil layers (raw humus from spruce, humus from beech, and peat) in a laboratory experiment with two fire regimes (to obtain BC and ash). These three types of organic soil layers are common and highly important organic layer types of boreal forests (Berg and McClaugherty 2008). Our hypothesis is that both fire treatments will result in a strong increase of P availability. Further, we hypothesize that the origin of the burned material determines the magnitude of P mobilization.

MATERIAL AND METHODS

Soil organic matter

Material from the soil organic layer (litter layer, uppermost 2 cm) of two different tree populations on

Dystric Cambisols, Norway spruce (*Picea abies*) and European beech (*Fagus sylvatica*), each sampling soil organic matter from different sites within the whole forest ($n = 10$), was collected in Tharandt Forest near Dresden, Germany. In addition, commercial white peat (*Sphagnum* spp.) of different sources ($n = 10$) was used. These three litter types were chosen because they represent litter detritus from the most relevant boreal ecosystems (coniferous forests, broadleaf forest, and peat bogs) (Berg and McClaugherty 2008). Prior to analysis and burning, litter was sieved using a 2-mm nylon sieve for homogenization and was subsequently dried at 40°C until constant mass. The carbon content was $47\% \pm 1.5\%$ for humus from spruce, $35\% \pm 3.1\%$ for humus from beech, and $48\% \pm 2.8\%$ for peat. Nitrogen content was $2.0\% \pm 0.1\%$ for humus from spruce, $1.8\% \pm 0.2\%$ for humus from beech, and $1.1\% \pm 0.1\%$ for peat. Total organic layer thickness was 8 ± 3 cm for raw humus from spruce and 4 ± 2 cm for humus from beech; typical thickness of peat ranges from a few centimeters to more than a meter.

Experimental setup

Soil fires vary in terms of temperature within the uppermost soil layer, where the maximum observed temperatures are up to 630°C (Schimmel and Granstrom 1996, Romanya et al. 2001). However, the standard temperature for the determination of loss on ignition is 550°C (DIN-EN-12879:2000 2001), which is also a commonly measured temperature during soil fire (Romanya et al. 2001). However, most fire temperatures in the field setting are lower, resulting in incomplete oxidation of organic material and subsequent formation of BC (temperature range 300–400°C). Fire duration also varies from minutes to hours, depending on oxygen availability; smoldering fires having durations of many hours are highly important for black carbon formation, with thick organic layers and ash formation being the end-product of incineration (complete oxidation) (Gonzalez-Perez et al. 2004, Bento-Goncalves et al. 2012). Consequently, we chose experimental conditions simulating fire conditions and duration resulting in BC treatment (350°C), ash treatment (Ash, 550°C), and no heating for the control treatment (C). The heat experiment was conducted until a constant mass was achieved (2–6 h) using a muffle furnace, with slow oxygen supply rates, which is comparable to smoldering wildfires (Flinn and Wein 1977). We burned and weighed the sample until the mass was constant. Because the experiment was conducted until constant mass was achieved, a maximal oxidation of the organic material at the specific temperature can be assumed to result in BC and ash characteristics comparable to those of natural fires.

P measurements

To determine the available phosphorus (P) fraction (indicated as P_i), the Bray-P and Olsen methods were

applied. The Bray-P method was applied for samples with $\text{pH} < 7$ (controls) to remove easily acid-soluble P forms. For the BC samples, as well as the ash samples ($\text{pH} > 7$), the Olsen-P method was applied. Briefly, for the Bray method, 2.5 g dry matter was extracted with 50 mL of a solution containing 0.03 mol/L NH_4F and 0.025 mol/L HCl (Bray and Kurtz 1945). Samples were soaked for 30 min, followed by shaking at 180 rpm for 10 minutes, and were subsequently filtered (low-phosphate filter, grade 131, Munktell, Germany). The method according to Olsen et al. (1954) was applied to remove dissolved and adsorbed P from calcium carbonate (and Fe-oxide surfaces). One g dry matter was extracted with 50 mL of a solution containing 0.5 mol/L NaHCO_3 (Olsen et al. 1954). Samples were soaked for 30 min, followed by shaking at 180 rpm for 30 minutes, and were subsequently filtered (low-phosphate filter, grade 131, Munktell, Germany). After filtration, 40 mL of the extract was neutralized by addition of 5 mL of 5 mol/L HCl and subsequently sonicated for 5 min (50 J/s) in order to remove CO_2 from the extract. A comparison of both methods clearly demonstrated that for BC and Ash treatments, the Bray-P method did not produce reliable results and had a low extraction efficiency (due to the high pH of the burned material, the assay pH was not constantly $\text{pH} < 3$ during soaking). Molybdate-reactive inorganic P content (Pi) in the extracts (Bray-P as well as Olsen-P) was measured photometrically with a continuous-flow autoanalyzer at 880 nm (Skalar Analytik GmbH, Breda, The Netherlands). The total (organic and inorganic) P content (Pt) of the extracts (Bray-P as well as Olsen-P) was determined by SPECTRO CIROS VISION ICP-OES (inductively coupled plasma optical emission spectrometer; Acme Analytical Laboratories, Vancouver, British Columbia, Canada). The total phosphorus content (TP) (acid digestion using aqua regia) of the three different soil organic matter types was analyzed by ICP-OES (DIN-EN-13346 2001).

Previous published data for fire effects on element availability (field data as well as laboratory experiments) are mostly related to the soil mass after burning (Turrión et al. 2010, Pereira et al. 2012, Ngoc Nguyen et al. 2014). However, element availability should be related to the initial mass prior to burning, because only this relation allows a correct and realistic interpretation of the fire effect on element availability. Here we present P availability data in relation to mass after burning and to the initial mass prior to burning.

Thermoanalysis and X-ray diffraction

Thermoanalysis and X-ray diffraction were performed on ash samples to characterize possible P-binding constituents. Thermoanalyses of the ashes were carried out by a simultaneous thermal analyzer, STA 409c/CD (Netzsch, Selb, Germany). Samples of about 50 mg were heated to 1000°C with a heating rate of 10 K/min under a constant nitrogen flow of 75 mL/min using Al_2O_3 as a

reference material. X-ray diffraction was performed using a Diffractometer FPM (Freiberger Präzisionsmechanik, Freiberg, Germany) RD7 (CuK_α radiation; Ni monochromator; angle range of 2–80° 2 θ , step scan 8.0 s, step sizes 0.02°) to characterize the ashes from the 550°C fire treatment. Zinc oxide was added to the ash as an internal standard with a final target concentration of 10–20%. We used the BGNM program to perform Rietveld refinement.⁶

Statistics

ANOVA and the Scheffé post hoc test were used for comparison of the data using SPSS version 21.0 (IBM, Armonk, New York, USA); all *P* values are from ANOVA unless otherwise specified.

RESULTS

Mass loss by fire treatments

A significant mass loss for all fire treatments and different litter types was found ($P < 0.001$; see Fig. 1). During the 350°C burning (resulting in BC), the mass loss was $64\% \pm 3\%$ (mean \pm SD) for raw humus from spruce, $54\% \pm 4\%$ for humus of beech, and $70\% \pm 3\%$ for peat. At 550°C (resulting in ash) mass loss was $89\% \pm 0.4\%$ for humus from spruce, $70\% \pm 1.4\%$ for humus from beech, and $93\% \pm 0.5\%$ for peat.

The total P (total P, acid-digested using aqua regia) content of the initial organic material was differed significantly between all litter types ($P < 0.001$). Spruce litter had 828 mg P/kg DM (dry matter), beech litter had 5100 mg P/kg DM, and peat 265 mg P/kg DM (Fig. 2).

The pH values for the initial organic material were significantly different ($P < 0.01$). Spruce litter had a pH of 3.9 ± 0.1 (mean \pm SD), beech litter pH was 3.3 ± 0.1 , and the peat pH was 3.1 ± 0.1 . During combustion at 350°C (resulting in BC), pH increased significantly ($P < 0.001$) to 8.5 ± 0.3 (spruce), 7.7 ± 0.3 (beech), and 9.6 ± 0.2 (peat). Combustion at 550°C (resulting in ash) increased the pH ($P < 0.001$) to 10 ± 0.2 (spruce), 9.4 ± 0.2 (beech), and 11.2 ± 0.1 (peat). The pH values were significantly different for BC and ash from the different litter types ($P < 0.001$).

Fire effects on P availability

Significant differences (ANOVA, $P < 0.001$; Scheffé post hoc test) between the fire treatments and the litter types were found for Pi (inorganic P within the extracts) related to initial mass prior to burning (Fig. 3). Inorganic P was lower for ash than for BC, but still higher than controls.

Relative to mass after burning, we found significant differences between all fire treatments and litter types ($P < 0.001$; see Appendix: Fig. A1). The Scheffé post hoc test revealed significant differences ($P < 0.001$) for all

⁶ http://programming.ccp14.ac.uk/solution/rietveld_software/index.html

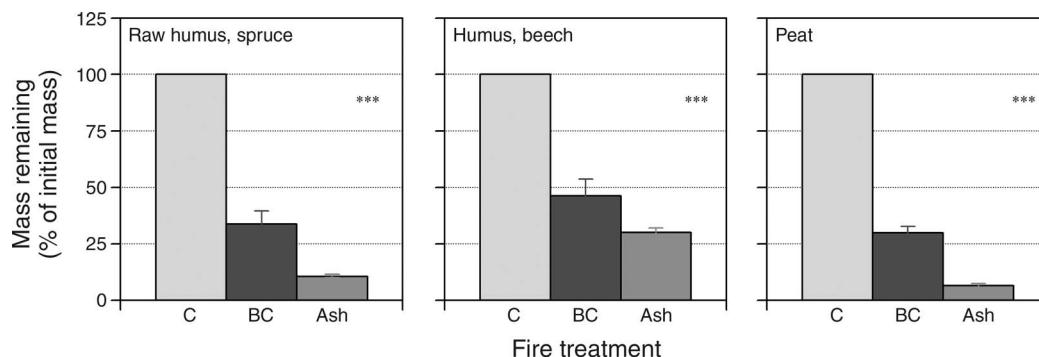


FIG. 1. Amount of mass remaining (mean \pm SE) of three types of organic matter after different fire treatments (C, control; BC, black carbon; Ash). Different fire intensities (differing in temperature and duration) transform the initial organic matter to either black carbon (formed at $\sim 350^{\circ}\text{C}$ by smoldering fire) or ash (formed at $\sim 550^{\circ}\text{C}$, full oxidation). We chose material from the soil organic litter layer (uppermost 2 cm) of Norway spruce (*Picea abies*) and European beech (*Fagus sylvatica*), collected in Tharandt Forest near Dresden, Germany, and commercial white peat (*Sphagnum* spp.) to represent litter detritus from coniferous forests (raw or mor humus), broadleaf forests (mull humus), and peat bogs, respectively. There were significant differences ($*** P < 0.001$) between all treatments.

fire treatments, except for comparison of BC and ash. The P_i values relative to mass after burning (or without burning for control) were lowest for the control treatment. Inorganic P from the BC treatment was significantly higher than P_i of the control treatment for all litter types. Likewise, P_i of the ash was significantly higher compared to the control treatment for all litter types.

For Pt (total P within the extracts) relative to initial mass prior to burning we found significant differences (ANOVA, $P < 0.001$; Scheffé post hoc test) between all fire treatments and litter types (Fig. 3). Total extractable P related to mass prior to burning for BC was highest. In addition, Pt of ash was higher than that of the control treatment, except for peat.

Relative to mass after burning (Appendix: Fig. A1) significant differences (ANOVA, $P < 0.001$) between the fire treatments and the litter types were found. The Scheffé post hoc test revealed significant differences ($P < 0.001$) for all treatments, except for comparison of BC and ash (not significant). Pt values relative to mass after burning (or without burning for control) were always lowest for the control; total extractable P of the BC treatment was significantly higher than that of the control treatment. In addition, Pt of ash was significantly higher than that of the BC treatment.

Because values of extractable P_i and Pt were of the same order of magnitude (P_i is $\sim 90\%$ of Pt), we used values of inorganic P for further calculations. Compared to the control samples, inorganic P (relative to mass prior to burning) significantly increased ($P < 0.001$) by burning to BC by 10-fold (spruce), ~ 10 -fold (beech), and ~ 17 -fold (peat) (Fig. 4), whereas heating to 550°C (Ash) significantly reduced inorganic P ($P < 0.001$) compared to BC, but still increased inorganic P related to control treatments by fourfold (spruce), sevenfold (beech), and twofold (peat).

The P_i values relative to the total P concentration of the bulk organic material (TP, acid-digested using aqua regia) of control samples prior to burning increased significantly ($P < 0.001$) by burning the controls to BC (Fig. 4). Further burning at 550°C (Ash) significantly reduced the extractable P_i proportion ($P < 0.001$). This means an increase in the proportion of P_i to TP by burning to BC of 10- to 16-fold and an increase from control to Ash of 2- to 7.5-fold. Certainly, we found high differences between the P_i /Pt values of the different extraction methods (Bray vs. Olsen) for the BC and Ash samples; the pH of BC and the ashes was too high for the Bray method (compare Fig. 3 with Appendix: Figs. A2–A5).

X-ray diffraction and thermoanalysis

X-ray diffraction pattern as well as thermograms of the ash samples revealed large differences between the types of organic matter (spruce, beech, and peat)

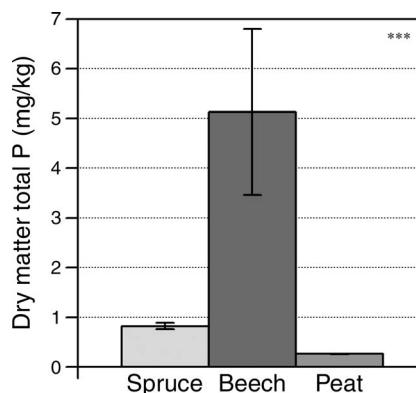


FIG. 2. Total P content (TP; mean \pm SE) after digestion in aqua regia of the different types of organic matter used in the experiments. There were significant differences ($*** P < 0.001$) between all organic matter types.

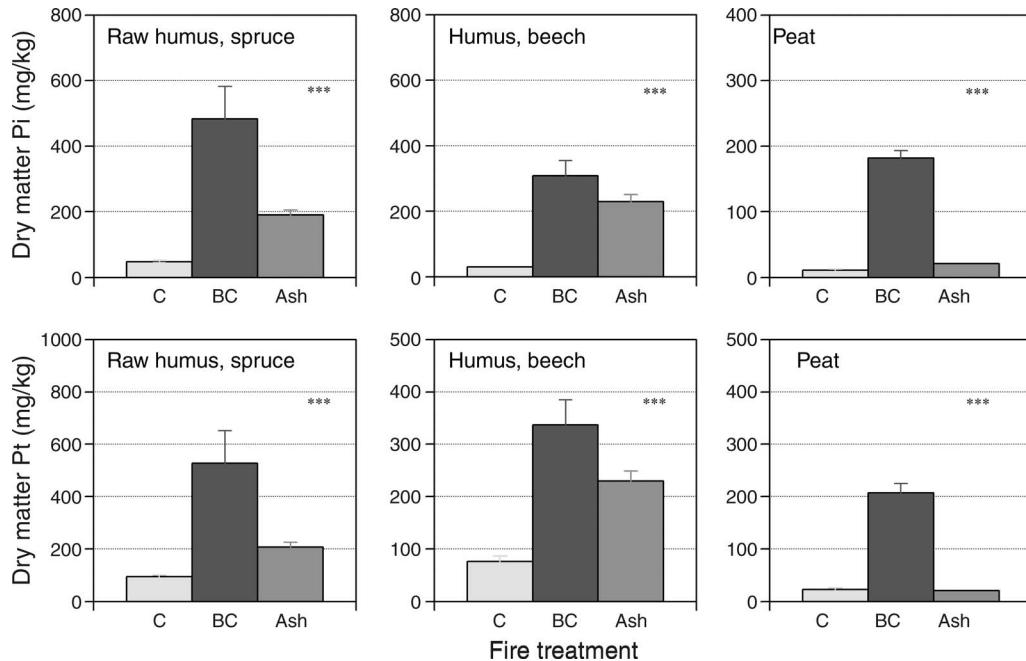


FIG. 3. Extractable inorganic phosphorus (Pi) and extractable total phosphorus (Pt, or Olsen-Pt) from the different types of organic matter after different fire treatments (C, control; BC, 350°C; Ash, 550°C) related to initial mass prior to burning; values are mean + SE. For the control, Pi and Pt were analyzed after Bray and Kurtz (1945); Pi and Pt of black carbon and ash were analyzed after Olsen et al. (1954) in view of substrate pH. There were significant differences (***) $P < 0.001$ between all treatments.

(Appendix: Table A1). The largest difference was found for the calcite content of the different ashes. By far, the lowest calcite content was found for ash from beech (1–2%), with much higher values for ash from spruce (7–9%) and peat (15.5–19.5%). We also found large

differences for crystalline SiO_2 content, as the litter types contained soil particles (spruce ash 12%, beech ash 59–63%, and peat ash 40%). Furthermore, the amorphous share (e.g., amorphous SiO_2) of the ashes was different (spruce 74–78%, beech 35–40%, and peat 40–

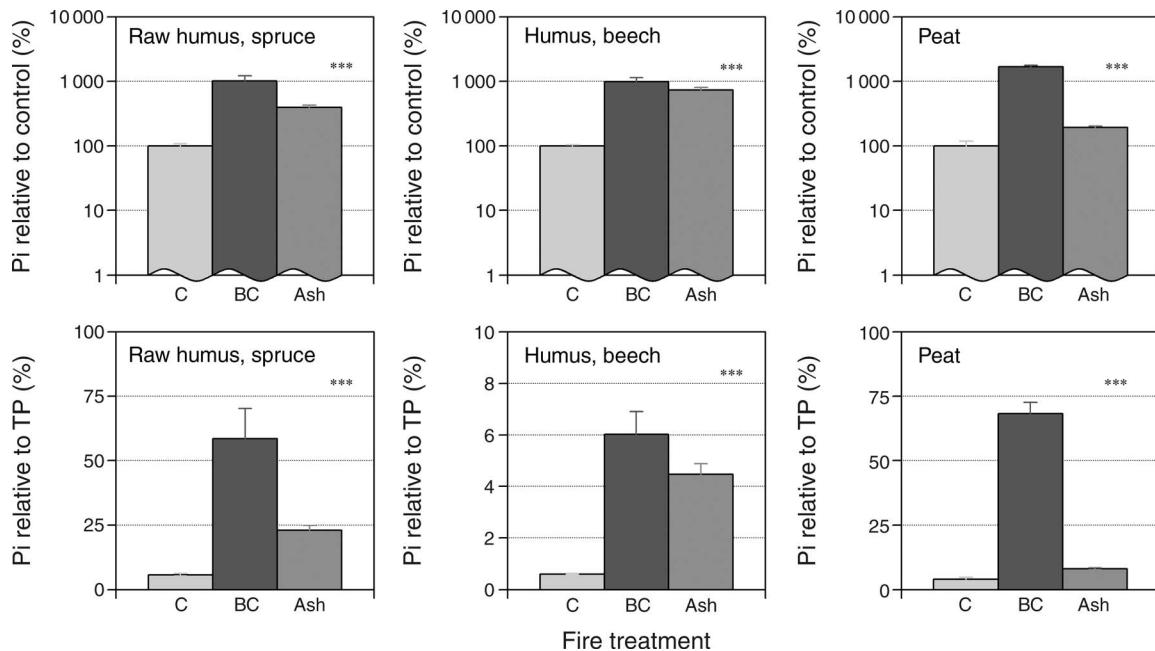


FIG. 4. Percentage availability of Pi (mean + SE) related to values of the control treatment and to total (bulk) phosphorus (TP) of initial soil samples. There were significant differences (***) $P < 0.001$ between all treatments.

45%). The thermograms (different heating steps) revealed low amounts of (1) adsorptive bound water, (2) silica-bound water, (3) organic and silica bound water, (4) calcite, and (5) amorphous silica (Appendix: Table A1). Thermograms of the control samples as well as the BC samples showed no differences between the different types of organic matter (data not shown).

DISCUSSION

Our results showed a clear increase of P availability by fire, confirming most other findings in this research field (Humphreys and Lambert 1965, Pereira et al. 2012, Ngoc Nguyen et al. 2014). We also demonstrated that the P availability in black carbon is similar to that in ash for the forest organic soil layer relative to mass after burning. However, our manuscript is the first to relate the P availability to initial mass of the organic matter prior to burning. Calculating P relative to the remaining mass after burning, as is commonly done, overestimates P availability by up to 14-fold. To avoid misleading interpretations of the absolute mobilization of P by fire, care should be taken when assessing available P from data related to mass after burning as is often reported (Humphreys and Lambert 1965, Ewel et al. 1981, Pereira et al. 2012, Ngoc Nguyen et al. 2014). For determination of P availability, both extraction methods (Bray-P and Olsen-P) were reported to be sensitive indicators for soil P availability for plants (Fixen and Grove 1990) and soil microorganisms (Demetz and Insam 1999). The P availability was strongly enhanced during 350°C burning to BC for all litter types. During burning of organic material to BC, the unavailable P is converted to available P (Certini 2005) and may be adsorbed to the anion exchange sites of the BC (organic phases with highly condensed carbon compounds, consisting of low amounts of hydrogen and high amounts of carbon) (Liang et al. 2006, Morales et al. 2013).

We found an increase of available inorganic P for the ash treatment; however, the increase was an order of magnitude lower than for the BC treatment (Fig. 3). The results obtained from X-ray diffraction as well as from thermoanalysis (Appendix: Table A1) suggest that the reduction of P availability from BC to ash was related to the calcite content of the ash. Decreasing P availability with increasing calcite content of ash was observed previously (Gonsiorczyk et al. 1998). Because the content and the absolute flux of Ca via litterfall are related to plant traits (Kattge et al. 2011), the life strategies of the respective plant species probably exert important effects on P availability after fire. However, the calcium impact on P availability may decrease over time due to acidification and dissolution of the calcite. Relating available P (Pi of the extracts) to the total P content (TP, acid-digested using aqua regia) of the organic material showed that the shift of P availability is independent of total P of the initial organic material. This was indicated by the beech samples, showing the lowest relative P availability despite a more than sixfold

TABLE 1. Average P stocks stored in different ecosystem components of comparable stands of beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*), from the present study and literature from representative stands of the Tharandt Forest or comparable areas in NE Germany.

Component	<i>Fagus</i>	<i>Picea</i>
Soil layer, Oe and Oa		
Soil mass (kg/ha)†	99.6	78.4
Total P (kg P/ha)‡	507.96	64.92
Plant-available P (kg P/ha)‡		
Control	1.49	1.96
BC	30.78	37.95
Ash	22.81	14.97
Litterfall P (kg P·ha ⁻¹ ·yr ⁻¹)§	3.95–9.77	1.54–2.71
Tree biomass P, 120-yr-old stand		
Total P, aboveground (kg P/ha)	65.90§	52.79§¶
Total P, harvested (kg P/ha)	97.80§	42.69§¶
P uptake by trees (kg P·ha ⁻¹ ·yr ⁻¹)	5.10–11.11§	3.14–8.21¶

† Koch and Makeschin (2004) calculated oven-dry (105°C) soil mass for each study site from six randomly arranged 10 × 10 m plots, each with a sample of the organic Oe and Oa layers composited from three subsamples taken in a 0.2 × 0.2 m frame.

‡ We calculated total P and plant-available Pi in organic soil layers by multiplying the dry mass of particular horizons (soil mass data from Koch and Makeschin 2004), by P concentrations from our three fire treatments (control, black carbon, and ash).

§ Litterfall data for *Picea* were from Dietrich (1963). Litterfall data for *Fagus* were compiled from Grunert (1964), who installed 10 1-m² litter traps per stand ($n = 3$) over a 5-yr period (P averaged over all seasons), and from Krauß and Heinsdorf (2008), who sampled 14 trees. All trees were harvested, tree biomass was determined for several subsections and components, and litter mass was determined by sampling green leaves. Based on these data, we developed allometric functions to estimate biomass of several components of *Fagus* as a function of tree dbh and tree height based on multiple linear regression analyses, and dependent on soil nutrient status. We calculated biomass stocks for a 120-yr-old *Fagus* stand and a comparable production potential class M28. Litterfall and annual P uptake represented a stand age range of 30–120 yr (M28). We also considered *Fagus* P uptake data from the literature survey of Jacobsen et al. (2003).

¶ For *Picea abies*, we calculated biomass, P in biomass, and P uptake for a 120-year-old stand (class M28) using biomass data based on growth models (production potential) compiled by Wenk et al. (1985) for the study region and P data from Jacobsen et al. (2003). We corrected biomass estimates assuming 26% tree crown biomass (Jacobsen et al. 2003) and applied a factor for *Picea* timber density of 377.1 kg/m³. Average P concentration of aboveground biomass was set as 0.014 mg P/g (Nebe and Herrmann 1987), a weighted-average P content proportional to the contribution of all tree components (stem, bark, crowns, leaves) to spruce aboveground biomass representative for the study area.

higher initial total P content. This may be explained by the immobilization of phosphate by calcite minerals, as suggested by the low mass loss of beech material during burning.

Because many terrestrial ecosystems (especially forests) burn regularly (Goldammer 1993, Kelly et al. 2013), the impact of fire on P availability is of general ecological significance. Altogether, our findings suggest a strong quantitative impact of fire on P availability within the respective ecosystems. Specifically, calculating the available P stocks in kg/ha (Table 1) reveals that

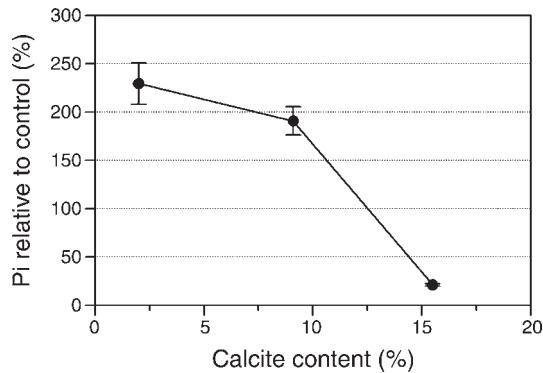


FIG. 5. Relationship between ash calcite content and percentage Pi (mean \pm SE) relative to the control, for the ash treatment only.

transformation of unavailable to available P by fire is on the same order of magnitude as the total P bound by aboveground biomass in spruce and beech ecosystems. The P release by fire exceeds that of weathering (0.005–3.0 kg P·ha⁻¹·yr⁻¹) from parent material (Binkley and Fisher 2012) and the mineralization of organic P (between 2.6 and 25 kg P·ha⁻¹·yr⁻¹) (Walbridge 1991, Saggart et al. 1998). Furthermore, transformation of unavailable to available P by burning is much higher than the annual cycling of P via litterfall and annual P uptake by forest biomass for the respective tree species (Table 1 and literature cited therein). With increasing P availability, the export of P from the soils to aquatic ecosystems potentially rises (Kreutzweiser et al. 2008) due to insufficient P uptake and subsequent reduced sequestration by plants (annual P uptake is lower compared to P mobilization by fire). Furthermore, ecosystem P stocks after fire may be reduced due to P loss by volatilization as suggested earlier (Kauffman et al. 1993), or rather losses of particulate-bound P via convection in fire-generated winds (Binkley and Fisher 2012). Consequently, ecosystem P stocks may be reduced at longer time scales due to enhanced leaching (until weathering recovers the former P availability), erosion, or losses of particulate-bound P via convection in fire-generated winds.

It is of high importance to relate the availability of P after burning to the initial litter mass prior to burning to avoid significant overestimation and, hence, incorrect interpretations and conclusions. We showed significant effects of fire on P availability of organic soil layers. The less available P of the initial organic matter was, to a substantial degree, mobilized as a fraction easily available for plants (Pi). Fire temperature had a significant impact on P availability. The intermediate fire treatment (BC, 350°C) caused the highest amount of P availability, whereas the more intensive fire treatment (incineration to ash at 550°C) increased the P availability to a lower extent than did BC. Consequently, fire temperature must be considered in regard to fires for fuel reduction (Agee and Skinner 2005), because low

temperature (smoldering fires) will strongly increase P availability and possible P export to adjacent ecosystems. Our data further suggest that the mobilization of P depends on the calcite content of the ash (Fig. 5), with calcite forming P forms of low solubility which, in turn, reduces easily available P. Altogether, the quantitative effect of fire on P availability is equally important as the annual P uptake by biomass and more important than mineral weathering for the respective forest ecosystems. As suggested by the percentage increase of P availability by fire, the origin of organic material (i.e., plant species) is an important determinant for the release of easily available P by burning. This importance is not associated with the initial P content but is probably related to the content of ions forming stable P forms (e.g., calcium-phosphates) not readily available to plants. Altogether, the impact of wildfires and fire temperature and its impact on P availability in topsoils must be considered in regard to the predicted change in fire regimes in the course of global climate change, with a potential strong increase of fire probabilities in some regions, but decreased probabilities in others (Krawchuk et al. 2009).

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SUPPLEMENTAL MATERIAL

Ecological Archives

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