

Effect of Scots Pine Forest Fire on Carbon, Phosphorus and Phosphatases Activity in Soil

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Abstract

The paper demonstrates seasonal changes in the content of organic carbon and phosphorus available to plants against the activity of phosphatases responsible for the transformations of that element in the soil caught by fire. The soil was sampled three times: April 2012, October 2012 and April 2013 from the surface horizon (0-15 cm) and subsurface horizon (15-30 cm), from four sites: from the site beyond the fire (control area), ecotone (border area) and from the soil burnt 150 m and 200 m away from the ecotone. The content of total organic carbon was the highest in the soil sampled 0-15 cm deep from the border area (ecotone) (16.77-23.11 g C kg⁻¹) as compared with the control and the area caught by fire. The highest available phosphorus content, irrespective of the sampling date, was recorded from the surface horizon 0-15 cm 200 m away from ecotone (74.08-85.02 mg P_{E-R} kg⁻¹) irrespective of the soil sampling date.

The activity of alkaline and acid phosphatase in the soil caught by fire was lower as compared with the control and ecotone in both horizons at all the research dates. There were reported significant negative values of the correlation between the content of available phosphorus in soil and the activity of alkaline ($r = -0.599$, $p < 0.05$) and acid phosphatase ($r = -0.583$, $p < 0.05$). The calculated factor of the changes in the activity of the enzymes investigated in time (TF > 1) showed that the process of soil regeneration was not completed a year after the fire. The calculated enzymatic index of soil pH (AIP/AcP) ranged from 0.35 to 0.77.

Key words: burnt, phosphomonoesterases, physicochemical properties, soil

Introduction

Forest wildfires are one of the most critical threats to forest ecosystems due to the shortage of forested areas and human pressure on the forests (Bircenas-Moreno et al. 2011). Changes in the intensity and timing of fires have, mainly through human influence (for example grass burning), induced a critical situation, where the few surviving forested areas face a serious risk of destruction in the event of a wildfire. Depending on the intensity, the fire changes the physical properties of soil, such as pH conditions, the content of organic matter and consequently the proportion and speciation of macro- and micronutrients, as well as composition of soil fauna and flora (Choromanska and DeLuca 2002, Certini 2005, Verma and Jayakumar 2012). Mineral compounds, which are formed during a fire event, are not immediately taken up, and therefore they can leach deep down in the soil profile resulting in a loss of nutrients from the uppermost soil layers (Certini 2005, Boerner et al. 2009). The changes can also lead

to an increase in the soil hydrophobicity resulting in a decrease in the water infiltration and an increase in surface runoff of water, which often increase soil erosion (DeBano 2000). High temperature also reduces or totally destroys soil microorganisms; hence causing a decrease in the intensity of biological soil processes and, a decrease in the enzymatic activity (Boerner and Brinkman 2003, Boerner et al. 2005). The effects of fire depend on its intensity and the duration as well as the changes in the soil properties can be favourable or harmful for the entire ecosystem (Hamman et al. 2008). Fires may also play a significant role in regulating ecosystem productivity and diversity by mineralization of nutrients stored in organic matter and allowing an invasion of rapid growing early succession species (Boerner et al. 2009). The activity of microbial enzymes involved in organic carbon and phosphorus metabolism can also decrease after burning (Docherty et al. 2012). The study of the activity of a number of soil enzymes facilitates the monitoring of the changes in soil due to stress factors and reculti-

vation, and as such they can be used as soil quality indices (Zhang et al. 2005, Olszowska 2009, Orczewska et al. 2012, Krzyżaniak and Lemanowicz 2013, Bartkowiak and Lemanowicz 2014).

The aim of this paper has been to evaluate the seasonal changes in the content of organic carbon and phosphorus available to plants against the activity of phosphatases responsible for the transformations of phosphorus in forest soil caught by fire due to an uncontrolled spring grass burning.

Material and Methods

Study area

The research was performed at a burned area located in the area of Fordon forests in Bydgoszcz, the Kujawsko-Pomorskie Province (Central Poland). The location of the Fordon Forest is determined by latitude (53°72' N) and longitude (18°62' E); the lowland climate is of moderate altitudes. The annual average temperature reaches 8.1-8.5 °C, with a monthly minimum in January (+1.9 °C) and the maximum in July (18.5 °C). Annual average rainfall reaches 580-650 mm and the growing season lasts for 215-225 days (compared with the 200 days being the average for Poland). Bydgoszcz is located on the left-bank erosion-accumulation berm of the Vistula glacial valley, which now flows about 4 km away north. The area is covered by a high sandy berm and transformed eolithic dunes. The burned area is about 10 ha; it was formed in March 2012 as a result of an uncontrolled spring grass burning. The fire was active for 6 hours.

The soil was sampled three times: April 2012, October 2012 and April 2013 from the specified observation areas dominated by the tree stands of Scots pine (*Pinus sylvestris* L.). Soil was sampled from 2 mineral horizons: 0-15 cm (humus horizons – A) and 15-30 cm (eluvial horizons – E) in three independent replications from four sites: from the site beyond the fire (from the control area), ecotone (border area) as well as the burnt soil 150 m away (point A) and 200 m away (point B) from the ecotone. The control area was appointed in the Scots pine tree stands neighbouring the burned area. The litter layer was not sampled. The sampling sites were determined with the dispersed point method. Each soil sample accounted for a mean value of 5 individual samplings. The air-dried soil samples of a disturbed structure were sieved through the Ø 2 mm sieve.

Soil analysis

Soil texture was determined using laser fraction method (Mastersizer 2000), pH was determined from 1 M KCl and H₂O soil suspension (ISO 10390), total organic carbon (TOC) was determined with a TOC

analyser Primas provided by SKALAR (since the most widely accepted estimation of soil humus is based on the determination of oxidizable organic carbon (% humus = % organic TOC × 1.724), studies on humus are invariably studies of total organic carbon. The content of available phosphorus (P_{E-R}) according to the Egner-Riehm method was determined with DL (PN-R-04023 1996), which involves the spectrophotometric measurement of the intensity of the colour of phosphorus-molybdenum blue created by orthophosphoric ions with molybdenum ions in the acid environment in the presence of SnCl₂. The activity of alkaline (AIP) [EC 3.1.3.1] and acid phosphatase (AcP) [EC 3.1.3.2] were detected according to Tabatabai and Bremner (1969) basing on the colorimetric determination of free substrate: *p*-nitrophenol after the incubation of soil samples for 1 h at a temperature of 37 °C.

Statistical analysis

With the values of the activity of alkaline and acid phosphatase reported, the enzymatic index of soil pH status (AIP/AcP) was calculated (Dick et al. 2000).

Based on the results, there was calculated the index of changes in the content of the total organic carbon and phosphorus and the activity of phosphatases in time (Time Index TI: April 2012/April 2013):

$$\text{Time Index (TI)} = \frac{\text{the concentration of the element in soil (April 2012)}}{\text{the concentration of the element in soil (April 2013)}}$$

where: TI < 0 means an increase, TI > 0 means a decrease in the content of carbon and phosphorus and the activity of phosphatases in soil, respectively.

The paper presents the arithmetic means of the results from three replications. Besides, the results of the analyses of the features investigated were exposed to the analysis of simple correlation ($P < 0.05$), which determined the degree of dependence between respective features. The correlation analysis was performed using STATISTICA 8.1 for WINDOWS *Pl*.

The coefficient of variation of the parameters analysed was calculated as follows:

$$CV = (S/X) \times 100 \%$$

where: CV is the coefficient of variation (%), S is the standard deviation, and X is the arithmetic mean.

Values within 0-15 %, 16-35 % ranges, and more than 36 % indicate low, moderate, or high variability, respectively.

Results

The granulometric fractions were dominated by sand from 2.0 to 0.05 mm in diameter. It allowed for

separating a single granulometric group with the sand content from 88.48 to 93.89 %, silt 5.58 to 10.27 % and clay from 0.14 to 0.94 % (according to USDA). According to the WRB Classification 2006, the soils of the Fordon Forest in Bydgoszcz are represented by Arenosols (Table 1). The soil pH-value of all samples indicated acidity (Table 2). Differences between our sampling sites might be caused by fire.

Table 1. Granulometric composition

Parameters	Fraction [%]		
	2.0-0.05 mm	0.05-0.002 mm	<0.002 mm
Minimum	88.48	5.58	0.14
Maximum	93.89	10.27	0.94
Mean	91.19	7.93	0.54

Table 2. Soil pH

Plot	Horizon cm	April 2012		October 2012		April 2013	
		pH _{KCl}	pH _{H2O}	pH _{KCl}	pH _{H2O}	pH _{KCl}	pH _{H2O}
Control	0-15	4.01	4.47	3.96	4.45	3.86	4.57
	15-30	4.22	4.53	4.25	4.86	4.30	4.68
Ecotone	0-15	4.78	5.37	4.65	5.23	4.56	5.19
	15-30	4.37	4.94	4.11	4.74	4.52	4.60
A*	0-15	4.96	5.48	5.01	5.64	5.25	5.70
	15-30	4.54	4.73	4.85	4.96	4.75	5.47
B**	0-15	4.99	5.53	4.78	5.27	4.38	5.12
	15-30	4.68	5.07	4.52	4.73	4.36	4.54

A* corresponds to the burned forest 150 m away from ecotone, B** corresponds to the burned forest 200 m away from ecotone

Table 3. Content of total organic carbon [mg C kg⁻¹] and humus [%] and available phosphorus [mg P_{E-R} kg⁻¹] in soil

Plot	Horizon cm	April 2012			October 2012			April 2013		
		TOC	Humus	P _{E-R}	TOC	Humus	P _{E-R}	TOC	Humus	P _{E-R}
Control	0-15	9.23	1.59	9.27	15.08	2.60	11.01	17.29	2.98	6.99
	15-30	3.90	0.67	6.82	4.42	0.76	7.56	4.42	0.76	1.65
Ecotone	0-15	16.77	2.89	39.00	19.24	3.31	42.36	23.11	3.98	26.49
	15-30	4.55	0.78	30.03	6.11	10.5	35.64	11.44	1.97	25.31
A	0-15	13.39	2.31	53.93	18.72	3.22	66.27	16.89	2.91	56.46
	15-30	5.72	0.98	34.44	6.11	1.05	44.01	7.15	1.23	30.76
B	0-15	12.22	2.10	74.08	10.01	1.72	85.02	14.56	2.51	82.86
	15-30	7.54	1.29	55.24	8.32	1.43	65.79	3.25	0.56	19.68
Mean		9.16	1.57	37.85	11.00	3.07	44.71	12.26	2.11	31.27
SD		4.06	0.79	23.07	5.89	3.04	27.40	6.96	1.19	26.60
CV		44.32	50.31	60.95	53.54	99.02	61.28	56.76	56.39	85.06

SD means standard deviation, CV means the coefficient of variation, TOC means total organic carbon, and P_{E-R} means available phosphorus

The content of total organic carbon was higher in the soil sampled 0-15 cm deep from the border area (ecotone) (16.77-23.11 g C kg⁻¹) than in the corresponding layer of the control (9.23-17.2 g C kg⁻¹) (Table 3). The calculated index of changes in the content of organic carbon in time (TF) (Table 5) showed an increase in the content of that parameter.

The concentration of phosphorus available in soil sampled immediately after the fire (April 2012) ranged from 30.03 to 74.08 mg P_{E-R} kg⁻¹. A wide range of the content of that element was connected both with depth and distance from the soil surface not caught by fire,

where the lowest concentration of P_{E-R} (6.82-9.27 mg P_{E-R} kg⁻¹) was recorded (Table 3). The highest concentration of P_{E-R}, irrespective of the sampling date, was recorded in the soil 200 m away from the ecotone (point B) (74.08-85.02 mg P_{E-R} kg⁻¹, 0-15 cm deep). With the ratio of the available phosphorus concentration in soil assayed directly after the fire (April 2012) to the content of that element in the soil taken up a year after the fire (April 2013), the index of changes in the content of P_{E-R} in time (TF) was calculated. There was found a difference in the content of phosphorus available in the 0-15 cm soil layers caught by fire (point A) (TF 0.96) and point B (TF 0.89) from ecotone (Table 5). A high variation (CV = 60.95-85.06 %) was observed for available phosphorus.

The activity of alkaline and acid phosphatase in the soil caught by fire was lower as compared to the control and the ecotone both in the surface and sub-surface horizons at the research dates (Table 4). In the surface horizons of the soils caught by fire (points A and B) there was a lower activity of alkaline and acid phosphatase, whereas on the control area beyond fire and in the border area the activity of phosphatases was higher in horizon 0-15 cm in comparison with the lower horizon (Table 4). Moderate variation was observed for the acid phosphatase (CV = 25.54-35.37 %). For the alkaline phosphatase the variation was high (CV = 37.41-59.80 %).

Based on the present results of the activity of alkaline and acid phosphatases, an index of soil effective pH was calculated (AIP/AcP) (Dick et al. 2000) (Table 4). The values of AIP to AcP ratio during the research was in the range of 0.45-0.77. The value adequate for crop plant growth and development can be considered to be 0.50 (Dick et al. 2000).

Boerner et al. (2005) and Zhang et al. (2005) showed an increase in the activity of acid phosphatase in the soil caught by fire as compared with the control soil in horizons 0-20 cm and 20-40 cm. However, we observed a decrease in the soil from horizon 40-

60 cm as well as an increase in the activity of acid phosphatase by 20 %-40 % in June, August and September.

The activity of phosphatases in soil caught by fire decreased in time (TF = 1.06 - 1.48 for alkaline phosphatase and TF = 1.07 - 1.54 for acid phosphatase) (Table 5).

On the basis of the analysis of simple correlation, there was a significant negative relationship between the concentration of phosphorus in soil and the activity of alkaline phosphatase ($r = -0.599, p < 0.05$) as

Table 4. Activity of alkaline (AIP) and acid (AcP) phosphatases [mM pNP kg⁻¹ h⁻¹]

Plot	Horizon cm	April 2012			October 2012			April 2013		
		AIP	AcP	AIP/AcP	AIP	AcP	AIP/AcP	AIP	AcP	AIP/AcP
Control	0-15	1.464	2.532	0.58	2.079	2.715	0.77	1.629	2.625	0.62
	15-30	1.000	1.991	0.50	0.911	1.724	0.53	0.992	1.656	0.60
Ecotone	0-15	1.271	1.966	0.65	1.331	2.084	0.64	1.241	1.939	0.64
	15-30	0.850	1.453	0.58	0.711	1.555	0.59	0.707	1.400	0.65
A	0-15	0.526	1.458	0.36	0.334	1.549	0.41	0.356	1.358	0.41
	15-30	0.712	1.586	0.45	0.540	2.086	0.35	0.576	1.032	0.43
B	0-15	0.495	1.147	0.43	0.552	1.282	0.43	0.465	1.026	0.45
	15-30	0.931	1.496	0.62	1.013	1.457	0.70	0.708	1.193	0.59
Mean		0.906	1.703		0.933	1.806		0.834	1.528	
SD		0.339	0.435		0.558	0.465		0.426	0.540	
CV		37.41	25.54		59.80	25.74		51.07	35.34	

SD means the standard deviation, CV means the coefficient of variation, AIP means alkaline phosphatase, AcP means acid phosphatase, AIP/AcP is the enzymatic index of soil pH

well as the activity of acid phosphatase ($r = -0.583, p < 0.05$) (Table 6).

The activities of alkaline and acid phosphatases negatively correlated with pH_{H2O} and pH_{KCl} of soil (Table 6). Hamman et al. (2008) recorded similar results ($r = -0.44, p < 0.01$). An increased amount of ash produced as a result of fire increased soil pH, however the mineral compounds decreased the activity of soil phosphatases because intensive supply of mineral phosphorus can lower the activity of phosphatase since e.g. an increased level of inorganic phosphorus in soil acts as a competition inhibitor decreasing the activity of enzymes.

Table 5. Factor of changes in the content of total organic carbon, available phosphorus and the activity of alkaline and acid phosphatases in time (TF)

Plot	Horizon cm	TOC	P _{E-R}	AIP	AcP
Control	0-15	0.53	1.33	0.90	0.96
	15-30	0.88	4.13	1.01	1.20
Ecotone	0-15	0.73	1.47	10.2	1.01
	15-30	0.40	1.19	1.20	1.04
A	0-15	0.92	0.96	1.48	1.07
	15-30	0.80	1.12	1.24	1.54
B	0-15	0.72	0.89	1.06	1.12
	15-30	2.30	2.81	1.31	1.25

Discussion

In this study, we characterized the response of the activity of phosphatases and the content of organic

Table 6. Person's correlation coefficients ($n = 24$)

	pH _{KCl}	pH _{H2O}	TOC	Humus	P _{E-R}	AIP	AcP
pH _{KCl}	-						
pH _{H2O}	0.867	-					
TOC	n.s.	0.452	-				
Humus	n.s.	n.s.	n.s.	-			
P _{E-R}	0.679	0.671	n.s.	n.s.	-		
AIP	-0.682	-0.551	n.s.	n.s.	-0.599	-	
AcP	-0.543	-0.468	n.s.	n.s.	-0.583	0.841	-

Significant at $p < 0.05$; n.s. is for non-significant, TOC is for total organic carbon, P_{E-R} is for available phosphorus, AIP is for alkaline phosphatase, and AcP is for acid phosphatase

carbon and phosphorus in soil to wildfires in forest. Our results indicate that wildfires affect the enzymatic activities and the soil content of TOC and P_{E-R}.

As reported in literature, fire strongly modifies the soil reaction and increases pH (Boerner et al. 2009, Certini 2005). A change in the reaction is due to an increase in the content of carbonates and hydroxides as well as due to considerable losses of organic acids as a result of high temperatures (DeBano 1991). High content of carbonates and hydroxides in ash originating from burnt plant material explains increase in pH values (Schafer and Mack 2010). The phenomenon of soil alkalization is short-term in nature and after a few years the soil reaction is similar to that before the fire (Knoepp et al. 2005).

The higher content of total organic carbon in the soil from the border area (ecotone) as compared with the control must have been due to the effect of the fire in the scope of lower temperatures (Fernandez et al. 1999). According to Gonzalez-Perez et al. (2004), the effect of fire on organic matter depends on its type and the intensity as well as on the soil moisture and soil type and the nature of burnt materials. Fire affects carbon cycling in forest soils directly by oxidizing many of the available compounds, and indirectly by changing environmental constraints on microbial activity. Most literature reports show that high temperature of fires triggers losses of the organic matter of soil by an average of about 50 % (Certini 2005, Fernandez et al. 2001) and at a temperature of 450 °C-500 °C

the losses of organic matter account even for 99 % (Neary et al. 2008).

Fire has an essential effect on an increase in the content of mineral phosphorus in soil by supplying a high amount of orthophosphates as well as the transformation of organic compounds of phosphorus to the mineral ones (Certini 2005, Knoepp et al. 2005, Turrion et al. 2010) and, therefore, P losses caused by evaporation are inconsiderable. However, an excessively intensive mineralization can be harmful since it leads to the immobilisation of an excessively high amount of phosphorus which, when not taken up by plants, gets leached to deeper soil layers. According to Qian et al. (2009), the content of nutrients of the areas caught by fire reflects also the species composition of the plants.

According to Hamman, the content of soil nutrients and biological activity after early and late season fire was different (Hamman et al. 2008). A similar relationship was reported by Hernandez et al. (1997), Boerner and Brinkman (2003), Olszowska (2009) referring it to the effect of high temperature on destruction and reduction of soil microorganisms and, therefore, a decrease in the intensity of microbiological processes of organic substance decomposition, including a decrease in the activity of soil enzymes (Boerner et al. 2005). In general, this trend is consistent with our results; the activity of the phosphatases was reduced against the control. However, Berber et al. (2013) found that surface fires have a limited effect on soil properties. Soil biological properties did not significantly change after fire; however, the season significantly affected the enzyme activities. It is connected with the content of total organic carbon, which induces and stimulates the biosynthesis of enzymes by soil microorganisms. In the surface horizon, there was a reduction in the population of microorganisms being the source of enzymes (Certini 2005). The enzymatic index of soil pH calculated on the present results of the activity of alkaline and acid phosphatases, can be used as an alternative method to determine soil pH as well as the changes in soil (Dick et al. 2000, Lemanowicz 2013, Lemanowicz and Bartkowiak 2013). The reductions in acid phosphatase activity were observed as paralleled increases in soil pH (Miesel et al. 2012). Usually the activity of phosphatases is inversely proportional to the content of mineral phosphorus in soil (Fukuda et al. 2001). An increased level of inorganic phosphorus in soil acts as a competition inhibitor decreasing the activity of phosphatases.

Conclusion

The content of available phosphorus was higher in the samples caught by fire both 150 m and 200 m

away from the ecotone. The uncontrolled burning resulted in a decreased activity of both alkaline and acid phosphatases in the surface and sub-surface horizons of the soil. The significant negative correlations between the activity of alkaline and acid phosphatases show a participation of those enzymes in the cycle of soil phosphorus. The calculated factor of changes in the activity of the enzymes in time (TF) showed that still one year after the fire, the process of soil regeneration was not completed. The reaction of the soil phosphatases, seen as a high decrease in their activity in burned areas, points to the applicability of the studies of enzymatic activity as a sensitive indicator of the soil reaction to stress factors. The research results allow for a closer look at the effect of fire on the ecochemical state of soils and hence a need to continue the research further in the future.

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