The Impact of Windthrow and Fire Disturbances on Selected Soil Properties in the Tatra National Park

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Abstract: In November 2004, forest stands in the Tatra National Park (TANAP) were affected by windthrow and in July 2005, the wildfire broke out on a part of the affected area. The objective of this study is to evaluate the impact of the windthrow and fire disturbances on soil microbial activity. Basal and potential soil respiration, N-mineralisation, catalase activity, soil microbial biomass, and cellulase activity were measured in soil samples taken from the A-horizon (depth of 0–10 cm) along 100 m transects established on 4 plots (reference site, burnt, non-extracted, and extracted sites) in October 2006. Some soil microbial characteristics exhibited a high spatial variability, especially microbial biomass and N-mineralisation. Significant differences in soil microbial characteristics (especially basal soil respiration and catalase activity) between plots were found. Generally, the highest microbial activity was revealed on the plot affected by fire. Soil microbial activity was similar on the extracted and non-extracted sites.

Keywords: windthrow; wildfire; spruce stands; forest soil; microbial activity

Wind and fire belong to those injurious agents that can damage individual trees, group of trees, or forest stands on a large scale (e.g., catastrophic windthrow). After these disturbances the environment, mainly microclimatic conditions, become usually changed – a greater input of precipitation, solar radiation and heat to the soil surface as well as a more intensive air circulation are observed. Catastrophic windthrows cause a complete destruction of the tree canopy, soil perturbation, and can initiate ground layer successions. Microtopography of the windthrow area is changed, pit-and-mound are formed. Major changes occur also in the soil moisture and often also in the soil structure in the topmost soil horizons. Some soil processes can be accelerated or, on the contrary, decelerated (Schatzel *et al.* 1989; Peterson *et al.* 1990; Ulanova 2000). Forest fires can affect many physical, chemical, mineralogical, and biological soil properties (water repellence, soil structure, bulk density, soil colour, quantity and quality of organic matter, soil acidity, etc.). The extent and duration of these effects depend upon the fire severity (its intensity and duration). Low to moderate severity fires promote the renovation of the dominant vegetation through the elimination of undesired species and transient increase of pH and available nutrients contents. No irreversible damage to the ecosystem occurs but the enhancement of hydrophobicity can render the soil less able to soak up water and more prone to erosion. Severe fires, such as wildfires, generally have several negative effects on soil. They cause a significant removal of organic matter, deterioration of both

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structure and porosity, loss of nutrients through volatilisation, leaching and erosion, and marked alterations of both quantity and specific composition of microbial and soil-dwelling invertebrate communities (Certini 2005).

In November 2004, spruce stands in the Tatra National Park (TANAP) on the area of 12 000 hectares were affected by a catastrophic windthrow and one year later (in July 2005) wildfire broke out on a part (220 ha) of this area (Fleischer *et al*. 2007). Based on a literature survey, we can suppose that, as a consequence of the changed microclimatic conditions, soil moisture and potentially also soil chemistry changes in the activity of the soil microorganisms can be expected. Because not enough information is available on the changes of the activity and structure of microbial communities on such disturbed plots, our study focused on the assessment of some characteristics of microbial activity on the windthrow- and fire-affected plots in comparison with the activity on a non-disturbed plot, and on assessing whether different microclimate and organic material input on the disturbed plots provokes changes in microbial activity.

MATERIAL AND METHODS

This study is a part of a broad investigation into the disturbance-induced changes coordinated by the Research Station of the TANAP (Slovakia). Four research plots, 100 ha each, were established, i.e. in an area where timber was extracted (EXT), a non-extracted site (NEX), a burnt site (FIR), and in a reference intact forest (REF). The characteristics of the study plots are given in Table 1. At the reference site, mature spruce stand was affected neither by windthrow nor fire. The extracted plot was destroyed by wind and the fallen trees were extracted. A large part of this plot has been overgrown by weeds, especially *Calamagrostis villosa.* On the burnt plot, fire completely destroyed the aboveground humus layer; however, mineral horizons were not affected by fire. A part of this plot is covered by an ash layer, whereas on other parts is bare mineral soil, ground-layer vegetation being scarce. The last plot (NEX) is a windthrow area, where fallen trees have not been extracted and the plot has been left to natural development. The ground-layer vegetation is slightly changed compared to the closed forest but light-demanding grasses and herbs do not predominate. More detailed information about the plant community composition and production was published by Simonovicova *et al.* (2007) and Soltes *et al*. (2007). The above-ground organic matter layer on the study plots (except the fire-affected site, where the organic matter layer was burnt down) is up to 10 cm thick; whereby mor is the dominant humus form.

Soil samples were taken at 10 m intervals along 100 m long transects from the A-horizon (0–10 cm) on each study plot in October 2006. All samples were stored at 4°C until laboratory analyses were performed. Prior to the analyses, the soil samples were hand-picked to remove rocks, plant roots, and discernible plant material. Soil moisture was determined gravimetrically by oven-drying fresh soil at 105°C overnight. Soil pH was measured in water and KCl suspension by a digital pH-meter. The content of organic matter was determined using Tyurin's method. Basal and substrate-induced respiration (Alef 1991), catalase activity (Chazijev 1976), nitrogen mineralisation (Alef 1991), and microbial biomass (Islam & Weil

Table 1. Characteristics of study sites

	REF	EXT	FIR	NEX
Altitude (m a.s.l.)	1100–1250	1040–1260	1000–1200	1050–1150
Aspect	SE	S	SE	SE-S
Slope (%)	10–20	10	5–10	5–10
Tree species composition (%)	spruce 80, larch 20	spruce 90, larch10	spruce 70, larch 30	spruce 70, larch 10, pine 20
Stand age	120/25	80	80	125/60/2
Soil type	Dystric Cambisol	Dystric Cambisol	Dystric Cambisol	Dystric Cambisol
Parental rock	moraine	moraine	stone-centered polygons	moraine

REF – reference site; EXT – extracted site; FIR – burnt site; NEX – non-extracted site; S – south; E – east

1998) were determined. Cellulase activity was determined on the basis of the decomposition of cellulose strips (laboratory assessment), the intensity of the decomposition was evaluated through optical density of the cellulose remains using the program Image J (Reinking 2007).

Statistical analyses were done using the statistical package SAS/STAT® (SAS 1998). The variability of the soil characteristics between the plots was evaluated using one-way analysis variance (ANOVA). Pairwise differences of the means between the plots were tested by Duncan's test.

RESULTS AND DISCUSSION

In Table 2, the basic statistical characteristics (mean values, standard deviation, coefficient of variation, minimal and maximal values) of the soil variables assessed are presented.

The variation in soil acidity was very small both between and within plots (*CV* ranged between 4.43% and 9.99%). At the reference site, pH/KCl was lower in comparison to the other sites; however, the differences between the plots were not generally significant (cf. Tables 3 and 4).

Table 2. Mean values, standard deviations (SD), coefficients of variation (*CV*), minimum (min) and maximum (max) values of the assessed soil characteristics on dry-weight basis (DW) at individual plots

Plot	pH/H_2O					pH/KCl				
	mean	SD	*CV*	min	max	mean	SD	*CV*	min	max
REF	4.07	0.32	7.99	3.60	4.54	3.35	0.33	9.99	2.73	3.82
EXT	4.26	0.19	4.43	3.98	4.57	3.47	0.15	4.31	3.18	3.66
FIR	4.25	0.24	5.68	3.97	4.67	3.38	0.27	8.10	3.02	3.78
NEX	4.34	0.26	5.93	4.04	4.72	3.61	0.29	8.13	3.29	4.14
	Gravimetric moisture (% w/w)					Organic carbon (%)				
REF	22.23	5.88	26.45	9.70	31.61	3.04	2.03	66.79	0.30	6.20
EXT	40.60	6.83	16.82	23.28	45.19	4.82	1.34	27.76	2.70	6.60
FIR	44.93	12.74	28.36	29.31	72.69	5.75	1.43	24.86	3.70	7.80
NEX	42.36	11.03	26.03	22.55	57.40	4.47	2.02	45.27	2.00	7.30
	Basal respiration (µg C-CO_2/g DW/h)					Potential respiration (glucose amendment) (µg C-CO_2/g DW/h)				
REF	0.06	0.03	44.00	0.03	0.11	0.29	0.11	37.13	0.15	0.53
EXT	0.08	0.03	41.90	0.04	0.16	0.40	0.20	49.33	0.02	0.72
FIR	0.15	0.05	34.84	0.07	0.22	0.56	0.20	36.54	0.28	0.99
NEX	0.11	0.04	34.72	0.08	0.18	0.34	0.06	17.46	0.27	0.42
	Microbial biomass carbon (µg C/g DW)					Catalase activity (ml O_2/g DW/min)				
REF	78.39	42.64	54.40	36.33	164.03	0.97	0.25	25.52	0.49	1.26
EXT	80.32	75.14	93.55	8.32	202.55	1.01	0.23	23.27	0.67	1.48
FIR	46.45	19.84	42.70	12.57	86.02	1.50	0.28	18.71	0.92	1.92
NEX	42.44	11.67	27.50	17.84	57.61	0.89	0.24	26.43	0.41	1.15
	N-mineralisation(µg N-NH_4^+/g DW/7 days)					Cellulase activity (OD)				
REF	4.79	1.18	24.60	3.22	6.68	173.09	4.11	2.37	164.40	178.27
EXT	1.94	1.06	54.53	0.61	3.68	174.16	7.91	4.54	159.83	186.73
FIR	5.26	3.36	63.93	1.44	13.63	177.30	9.36	5.28	167.63	194.47
NEX	5.61	2.82	50.21	2.85	11.81	172.63	10.55	6.11	159.33	193.67

REF – reference site; EXT – extracted site; FIR – burnt site; NEX – non-extracted site

Soil organic carbon exhibited a higher variability than soil acidity. The highest within-plot variation (CV = 66.79%) was found at the reference site. Surprisingly, the lowest organic carbon content was observed at the reference site, differing significantly from the other plots. The highest organic carbon was found at the burnt site.

Significant differences ($P < 0.001$) were observed in the soil water content. Soil moisture at the reference site was approx. half those on the other plots.

Between soil microbial characteristics, significant differences were found in basal respiration and catalase activity ($P < 0.001$), potential respiration and N-mineralisation ($P < 0.01$). On the other hand, differences were nonsignificant in cellulase activity and microbial biomass (Table 3). The highest basal and potential respiration rates were found at the burnt plot, the lowest ones at the reference site. Both characteristics exhibited also a high within-plot variation. As to microbial biomass, the situation is different. Among all microbial activity indicators

Table 3. Analysis of variance of soil variables (F-tests)

Factor	Degree of freedom	Sum of squares	Mean square	F-test
pH/H_2O				
plots	2	0.39	0.13	1.93ns
error	35	2.33	0.07	
pH/KCl				
plots	3	0.39	0.13	1.77ns
error	35	2.57	0.07	
Soil organic carbon				
plots	3	37.87	12.61	4.23*
error	35	104.31	2.98	
Soil water content				
plot	3	3192.97	1064.32	11.77***
error	35	3164.74	90.42	
Basal respiration				
plots	3	0.04	0.01	9.30***
error	35	0.05	0.00	
Potential respiration				
plots	3	0.41	0.14	5.59**
error	35	0.85	0.02	
Microbial biomass carbon				
plots	3	11895.79	3965.26	1.93ns
error	35	71814.96	2051.86	
Catalase activity				
plots	3	2.26	0.75	11.94***
error	35	2.21	0.06	
N-mineralization				
plots	3	82.51	27.50	5.13**
error	35	187.78	5.37	
Cellulase activity				
plots	3	130.15	43.38	0.63ns
error	35	2394.69	68.42	

Significance levels: ***$P < 0.001$; **$P < 0.01$; *$P < 0.05$; ns – non-significant

Table 4. Duncan's pairwise test of the differences of means between plots (the plots with the same capital letters do not differ significantly)

Plot	pH/H_2O	pH/KCl	Organic carbon(%)	Gravimetric moisture (% w/w)	Basal respiration (μg C-CO_2/g DW/h)
REF	4.07 B	3.35 A	3.04 B	22.23 B	0.06 C
EXT	4.26 A	3.47 A	3.04 B	40.60 A	0.06 C
FIR	4.25 A	3.38 A	5.75 A	44.93 A	0.15 A
NEX	4.34 A	3.61 A	4.47 A	42.36 A	0.11 A B
	Potential respiration (μg C-CO_2/g DW/h)	Microbial biomass C (μg C/g DW)	Catalase activity (ml O_2/g DW/min)	Nitrogen mineralisation (μg N-NH_4^+/g DW/7 days)	Cellulase activity (OD)
REF	0.29 B	78.39 A	0.97 B	4.80 A	173.09 A
EXT	0.40 B	80.32 A	1.00 B	1.94 B	174.16 A
FIR	0.56 A	46.45 A	1.50 A	5.26 A	177.31 A
NEX	0.34 B	42.44 A	0.89 B	5.61 A	172.63 A

REF – reference site; EXT – extracted site; FIR – burnt site; NEX – non-extracted site

assessed microbial biomass exhibited the highest overall variability (CV = 27.5–93.55%). The highest average values were found at the extracted and reference sites, being twice as high as at the non-extracted and burnt sites. However, with regard to a very high spatial variability, the differences between the plots were insignificant.

The lowest within-plot variation was observed in catalase activity (CV = 18.71–26.43%). Significantly, the highest activity was found at the burnt plot (Table 4).

N-mineralisation also belongs to the parameters with a considerable variation within the study plots (CV > 50%). Significantly, the lowest N-mineralisation was observed on the extracted plot; the highest values were found at the non-extracted and burnt sites.

Cellulose decomposition was very slow; during a three-month observation period, almost no decomposition was recorded although cellulose strips were colonised by soil microorganisms (mainly fungi).

The soils on the study plots were very similar (Dystric Cambisol). They did not differ in the soil acidity; the starting conditions were supposedly very similar. After wildfire, changes in the soil properties frequently occur, e.g., increased soil pH (Certini 2005) as a consequence of the release of mineral nutrients after the burning down of organic material. However, the contents of these elements depend on the quality of organic material – the litter from deciduous trees is richer in base elements than that from conifers. Because spruce and larch were the dominant tree species on our experimental plots, we did not expect an increase of soil pH after fire, which was confirmed by our observations.

Organic carbon content was the lowest at the reference site, whereas it was significantly higher on the disturbed plots. A positive long-term effect of the forest fire on the content of soil organic carbon was observed by Johnson and Curtis (2001). The authors suggested three reasons for this increase – the incorporation in the mineral soil of unburnt residues, which are more protected from biochemical decomposition, the transformation of fresh organic materials to more recalcitrant forms, and a frequent colonisation of the burnt areas by nitrogen-fixing species. However, our measurements were performed quite shortly after the disturbances (1 year) and no older records are available for the sites investigated. In fact, we do not know whether a higher organic C content on the disturbed plots has been really caused by the disturbances or whether these differences existed before the disturbances occurred.

The significantly lowest soil moisture at the reference site is probably due to greater losses of water through transpiration and interception of standing trees. The interception in spruce stands can account up to 34–38% of the total precipitation. Water desuction due to tree transpiration may also represent more than 30% of total precipitation (Petrík *et al.* 1986; Pichler 2006; Pichler *et al.* 2006).

Generally, soil microbial characteristics exhibited a high spatial variability, especially microbial biomass and N-mineralisation with *CV* > 50%. This is not surprising as microbial characteristics are known to vary more in space and time than other soil physical and chemical properties (Mäder *et al*. 1993; Gömöryová 2004).

For most of microbial characteristics, the pattern was quite consistent – the highest activity was found on the disturbed plots, especially those disturbed by fire. Such a trend was observed in basal respiration, substrate-induced respiration, and catalase activity. With microbial biomass and N-mineralisation, the pattern was different, but it was already mentioned that these two parameters exhibited also a higher spatial variability. Windthrow does not influence microbial biomass or activity directly but rather through the changed environment (soil moisture, temperature, nutrient status, etc.). In contrast, wildfire directly reduces microbial biomass through high temperature (Certini 2005). The direct influence of fire depends on the fire intensity and duration and also on its type (underground – ground fire). We supposed that on the disturbed plots, changes in microbial biomass would be observed as a consequence of the changed microclimate. However, this assumption was not confirmed. The higher microbial biomass at the reference and extracted sites can be associated with a higher root density in the topsoil and a higher number of microorganisms near to the roots.

Generally, microbial activity on the disturbed plots was higher than that at the reference site. Basal respiration and catalase activity were especially high at the burnt plot. Wright and Coleman (2000) stated that soil respiration is closely related to soil temperature and moisture and, at the sites open after disturbances, higher soil respiration was observed as a consequence of a higher topsoil temperature and more extreme fluctuations of soil moisture. At the same time, soil respiration is also associated with the soil organic matter content and availability. In our study, the highest basal soil respiration at the burnt site could be explained also by high organic matter and water contents and probably also by the changed temperature regime as compared to the standing closed stand (reference site). Catalase activity is associated with these factors as well (Beck 1971). On the other hand, a low microbial activity at the reference site can be explained by lower soil water and organic matter contents, and probably also by lower air and soil temperatures below the forest canopy. We expected to observe differences in soil microbial activity at the extracted and non-extracted sites as a consequence of different ecological conditions. The tree removal increases insolation to the ground and changes soil water regime by altering the rates of evaporation and transpiration, and eliminating interception of precipitation by the canopy. These relatively immediate changes in soil microclimate may directly alter the composition and the activity of the soil microflora (Boyle *et al*. 2005). On the other hand, retaining of fallen trees and coarse woody debris on the plot also leads to changes in ecological conditions as the fallen trees shadows affect the water and temperature regimes, and there is a considerable amount of organic material lying on the ground and gradually decomposing. However, we did not generally observe differences between these plots in the soil microbial characteristics. We suppose that the main (principal) changes occurred in the surface organic matter layer, whereas for the mineral A-horizon, the time after the disturbances has been too short for significant changes in microbial activity to appear. Only at the FIR plot, where the aboveground layer was completely destroyed, changes in some soil microbial indicators were observed. Nevertheless, the changed ecological conditions on the disturbed plots will be reflected also in the composition and production of the herb layer because of different trajectories of the secondary succession and, consequently, in the abundance and composition of soil microorganisms (Kang & Mills 2004).

CONCLUSIONS

These preliminary investigations indicate that differences occur in soil microbial activity at the disturbed plots in comparison with the intact forest. At the FIR plot, a thick aboveground humus layer was completely burnt down so that the mineral nutrients were released into the mineral A-horizon. Water and temperature regimes also changed: apparently, despite increased fluctuations, a higher access of solar radiation onto the soil and at least temporarily increased moisture were beneficial for the soil microorganisms. Soil microbial activity was similar at the extracted and non-extracted sites. Additional data in next years will be needed to determine whether the changed conditions at the windthrow plots, will be reflected also in a changed microbial activity of in deeper parts of the soil profile.

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