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Soil enzymatic activity in artificially and naturally regenerated forests after wind damage in north-eastern Poland

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Abstract. The aim of the study was to describe biochemical reactions in the soil based on the activity of urease and dehydrogenases in Scots pine stands damaged during and differentially managed after hurricanes. Soil enzymatic activity was investigated in 2005 and again in 2013 for selected stands in the Pisz Forest District where wind damage occurred in 2002. Most of the damaged stands were cut down and replanted, but 445 ha were left untouched for study purposes. The investigated areas differed with respect to stand damage and management. The enzymatic activity correlated well with the content of organic matter which was higher in organic than in mineral soils. In the area left to regenerate naturally, dehydrogenase and urease activity was higher in 2013 compared to 2005, which suggests the improvement of site conditions. The values of the examined biochemical parameters were correlated with the type of forest regeneration, with the forest soil regeneration being higher in artificially than in naturally regenerated stands. Changes of soil enzymatic activity were correlated with the level of stand damage and the type of management after wind damage.

Keywords: wind damage, urease, dehydrogenases, forest soils

1. Introduction

Large-scale disturbances, such as fires and hurricanes, are inevitably connected with the forest ecosystem processes, and the after-effects of such events allow for studying the forest natural regeneration (Dobrowolska 2006). In wind-throw- affected stands, with high amounts of strongly insolated deadwood and the dried out soil and litter, there increases the heterogeneity of microhabitat conditions. The usual processes of accumulation and decomposition of dead organic matter are altered and the ecosystem is transformed. This is not without the consequences for the microorganism communities in the soil (Ulanowa 2000). In terrestrial ecosystems, edaphic qualities, soil microorganisms, and vegetation cover remain in close interdependence. The development of fitting microorganism communities and vegetation formations is determined by the soil physico-chemical properties. The processes of microbiological mineralisation of the soil organic matter assure availability of macronutrients indispensible for plant growth; therefore, it is assumed that the soil microbial activity is strongly associated with ecosystem fertility and productivity. Additionally, microbial biomass constitutes nutrient source and storage for plants; thus, it is an essential factor that determines soil fertility (Leiros et al. 2000; Baldrian et al. 2010). The soil biological activity is considered to be a good indicator of soil quality. The evaluation of the enzymatic activity allows for determination of soil regeneration rates in wind- damaged areas. Little is known about the soil enzymatic activity in the early stages of ecosystem functioning after stand-replacing wind-throw and later soil dynamics.

The aim of the study was to determine the intensity of the soil biochemical changes based on evaluation of urease and dehydrogenase activities in the soil in wind-throw- affected Scots pine stands with different levels of wind damage and different forest management practices applied afterwards.

2. Study area

The study on the soil enzymatic activity was conducted in the years 2005 and 2013, in chosen stands under manage-

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ment of the Pisz forest district (Pisz FD), located in north-eastern Poland (21°38'–22°03'E; 53°28'–53°46'N). Pisz FD forests are an integrant part of the Puszcza Piska forest. In reference to The Natural – Forest Regionalization of Poland 2010, Pisz FD is placed in the Second Natural-Forest Region (II. Mazury-Podlasie), in the Masurian Forests mesoregion (II.4) (the Forest Inspectorates: Szeroki Bór and Wilcze Bagno and parts of the Forest Inspectorates: Pisz and Dłutowo), and also in the Great Masurian Lakes mesoregion (II.3) (a part of the Forest Inspectorate Pisz) as well as in the Ełk Lakeland mesoregion (II.6) (a part of the Forest Inspectorate Dłutowo) (Zielony, Kliczkowska 2010). The region has glacial soils, mainly — sands, sandurs, and glacial tills. The largest part of Pisz FD is covered by rusty soils (subtype: podzolic). Scots pine *Pinus silvestris* L. is a dominant tree species in the forests managed by Pisz FD.

In July 2002, hurricane winds broke or uprooted tree stands on 33 thousand ha of Pisz FD. In most cases, wind-damaged trees were removed and the area was reforested; however, for scientific purposes, 445 ha of the wind-throw-affected stands remained unmanaged. The plots studied were different with regard to the extent of stand damage and the type of management applied after wind-throw. There were established 12 study plots in the zone with damage below 10%, 11 study plots in that with 11%–50% damage, and 10 study plots in that with 90% damage. For purposes of comparison, there were also established five study plots in the reforested area (planted 1 year after the hurricane). The size of all the experimental plots was 100 m^2 (Table 1).

3. Material and research methods

For the assessment of enzyme activities, there were taken soil samples at the organic (O) and humus (A) horizons in the study area 'Szast'. In the years 2005 and 2013, in the reforested area (tree plantation established 1 year after the hurricane), mixed soil samples (comprising 5- cm thick mineral soil layer) were taken from tree rows and the spacing in between the rows. Besides, in 2013, a mixed soil sample (from tree rows and the spacing in between) from the newly formed organic horizon was collected. The assessment of the soil enzymatic activity was performed on air-dried soil samples put through a 2-mm sieve. The urease activity was determined with the use of the colorimetric technique and expressed as N-NH_4 mg in 10 g of soil per 48 h. Dehydrogenases were determined with the use of the colorimetric technique and their activities were expressed as triphenylformazan (TPF) mg in 10 g of soil per 24 h (Russel 1972).

The mean values of the soil enzymatic activities were pairwise compared in the experimental blocks, with the use of the paired t-test at $p < 0.05$. The differences among the study plots were determined with the Kruskal–Wallis test. All calculations were performed using *STATISTICA* ver. 6.0 (StatSoft, Inc. 1997).

4. Results

The activities of the soil enzymes studied — urease and dehydrogenases — were strongly associated with soil contents of organic matter, as the enzymes showed higher activities in the organic (O) horizon than in the humus (A) horizon (Fig. 1-4).

Equally, at the organic and humus horizons, the urease activity was the highest in the area reforested 1 year after the hurricane, and the lowest in the stand severely damaged and not cleared away (with not removed wood — DrN) (Fig. 1-2).

In the reforested area, in the humus horizon, the urease activity was slightly higher in the year 2013 than that observed in 2005. In the year 2013, there was observed very high urease activity in the newly formed organic soil horizon (which did not exist in 2005).

In all the stands studied in the protected forest 'Szast', in both soil horizons examined, the urease activity was higher in 2013 than that in 2005. In the humus horizon, in slightly damaged tree stand (S), the urease activity was significantly

Table 1. Research plots on blowdown area in Piska forest

Localization	Compartment	Type of management and level of stand damage	Species composition	Age	Site type
Szast	118 d	tree stand slightly damaged (<10 %)	So	104	Bśw
Szast	104a	tree stand moderately damaged (11–50 %)	So	54	Bśw
Szast	100a	tree stand severely damaged with removed wood (>90 %)	So	52	Bśw
Szast	99b	tree stand severely damaged with left wood (>90%)	So	55	Bśw
Jeże	113	cultivation	So	12	Bśw

So – pine, Bśw – fresh coniferous forest

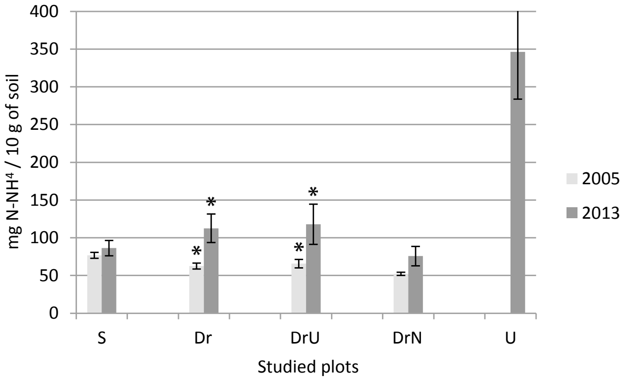

Figure 1. Changes of the urease activity of the organic horizon on research plots ± standard error. Significant differences between averages from 2005 and 2013 were marked * at p < 0.05, S – tree stand slightly damaged, Dr – tree stand moderately damaged, DrU – tree stand severely damaged with removed wood, DrN – tree stand severely damaged with left wood, U – cultivation.

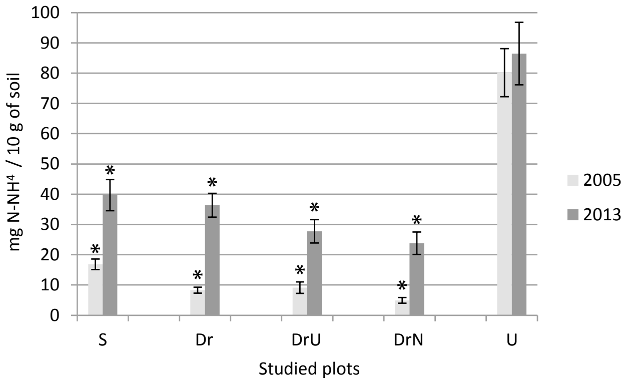

Figure 2. Changes of the urease activity of the humus horizon on research plots ± standard error. Significant differences between averages from 2005 and 2013 were marked * at p < 0.05. Designation as in Figure 1.

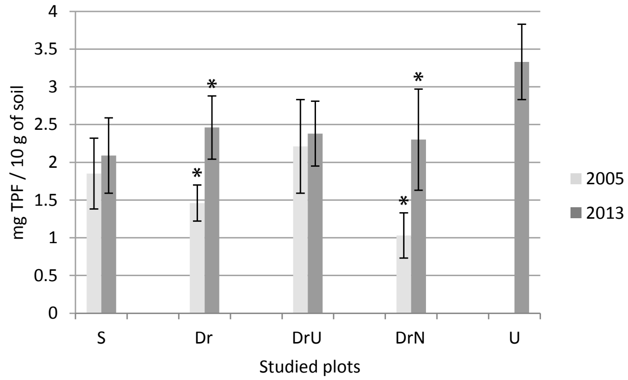

Figure 3. Changes of the dehydrogenases activity of the organic horizon on research plots ± standard error. Significant differences between averages from 2005 and 2013 were marked * at p <0.05. Designation as in Figure 1.

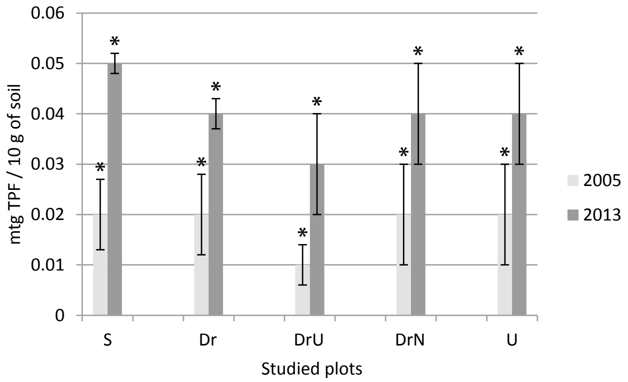

Figure 4. Changes of the dehydrogenases activity of the humus horizon on research plots ± standard error. Significant differences between averages from 2005 and 2013 were marked * at p <0.05. Designation as in Figure 1.

higher (t = 4.06) in 2013 than in 2005. In the stand moderately damaged (Dr), significant differences between the years of observation were found for the organic horizon (t = 2.7) and the humus horizon (t = 7.9). In the stand severely damaged and cleared away (with removed wood – DrU) as well as the stand severely damaged and not cleared away (with left behind wood – DrN), a significantly higher (t = 4.5) urease activity was observed in 2013 in the humus horizon than that in 2005 (Fig. 2).

The changes in the dehydrogenase activities were similar to those observed in the urease activities. In the areas with natural forest regeneration, in both soil horizons studied, the dehydrogenase activities were higher in 2013 than those in 2005. In the artificially reforested area, in the humus horizon, dehydrogenase activities were two-fold higher than those observed in 2005. Similar to the urease activity, the dehydrogenase activities were the highest in 2013, in the newly formed organic horizon in the reforested area (Fig. 3–4).

In the organic horizon, significantly higher (t = 2.56) dehydrogenase activities were observed in the stand moderately damaged (Dr) as well as in the stand severely damaged and not cleared away (DrN) (t = 2.02) (Fig. 3). In the stand slightly damaged (S), the dehydrogenase activities were increased significantly (t = 3.44) in the humus horizon. Significantly higher dehydrogenase activities were observed in the humus horizon in the stand severely damaged and cleared away (DrU) as well as in the stand severely damaged and not cleared away (DrN) (t = 3.55 and t = 4.5, respectively) (Fig. 4).

5. Discussion

The soil biological activity was tested based on the commonly used parameters linked with vital microbial functions in forest, that is, soil mineralisation processes. The activities of the enzymes studied were strongly connected with the soil organic matter contents, as significantly higher enzyme activities were observed in the organic horizon than in the humus horizon in the soils of the studied forest stands. Numerous literature data (Leirós et al. 2000; Šnajdr et al. 2008; Zwoliński 2008; Olszowska 2010) confirm a strong relationship between the development of soil microorganisms, as well as soil enzymatic activity, and soil contents of organic carbon – basic energy substrate for microorganisms in the soil.

In the wind-throw- affected areas, the conditions of soil environment, including soil microclimate, are altered, and increasing temperature enhances the rate of organic matter decomposition (Hyvönen et al. 2005). There are available, the results of several studies that show carbon balance alteration due to land use change, mainly on account of deforestation (among others: Guo & Gifford 2002, Laganière et al. 2010). However, a small amount of data is available on carbon changes as a consequence of sudden and unforeseeable natural disasters. The subject literature shows that not many studies have been hitherto conducted on the soil enzymatic activity in the areas impacted by a natural disaster, such as a hurricane. Błońska and Lasota (2014) showed significantly lower dehydrogenase and urease activities in the wind-throw- affected areas, where the biological balance of the soil environment was disturbed. Kramer et al. (2004) as well as Thürig et al. (2005) demonstrated a decrease in the organic carbon during some decades after the wind-throw. Likewise, a study by Don et al. (2012) concerns the changes in the organic carbon contents in different soil horizons, which occurred in the area affected by a hurricane. A little is known about the soil enzymatic activity at early stages of functioning of the ecosystem affected by the wind-throw. The results of the present study indicate that the activities of the enzymes studied fluctuated, depending on stand damage extent, stand density, and forest management practice applied after the hurricane. All these factors affected the humidity, temperature, and oxygenation of the soil examined. The dehydrogenase and urease activities observed in the present study were associated with the stand age. As organic matter changes more intensely in younger tree stands, the highest activity of the soil enzymes tested was observed in the reforested area with young trees. Also, the dehydrogenase activities were high in the moderately damaged tree stand with left behind wood, and this can indicate that the remnant forest affected the soil enzymatic activity. In 2005, there were found no significant differences in the activities of the enzymes studied in the hurricane- affected tree stands in the protected forest 'Szast'. The analysis of the soil enzymatic activity, carried out in the year 2013, showed directions of the biochemical changes within differently managed forest plots. The reduction in the tree density in the wind-throw- affected protected forest 'Szast' resulted in an increase in the soil enzymatic activity. In 2013, the dehydrogenase and urease activities were higher in naturally regenerating forest areas than in 2005, and this may indicate a gradual improvement of the site conditions. Likewise, studies by Gömöryová et al. (2011, 2014) showed a significant enhancement of the soil microbial community response as well as an increase of catalase activity on the monitoring plots on the wind-throw areas, which indicated a gradual recovery of soil microorganisms.

As the microbial response to environmental factors is quicker than that of other living organisms, the assessment of the soil biochemical parameters allows for an early detection of soil improvement, before changes of the soil physico-chemical properties grow to be visible. In the present study, in both observation years (2005 and 2013), there were observed significant differences between the reforested area (planted 1 year after the hurricane) and the plots studied in the protected forest 'Szast'. Artificial regeneration of the wind-throw- affected forest areas resulted in significant changes in the activities of the soil enzymes studied – distinctive in the year 2013, that is, 11 years after the hurricane damage. The altered site conditions within this period of time and the highest soil enzymatic activity were detected in the area with trees planted after the hurricane damage. This effect has been observed up until now.

At the same time, in line with the results obtained by Dinesh et al. (2004), Nourbakhsh (2007), and Lagomarsino et al. (2011), the soil enzymatic activity is a sensitive indicator of the soil changes caused by different forest management practices. The biochemical indicators can be very useful in comparative studies on soil quality or on soil response to a range of environmental factors (biotic and anthropogenic). This was confirmed by the research carried out on not managed and naturally regenerating wind-throw- affected areas. Such results support the increased use of biochemical indicators in research on forest soils – especially, in the evaluation of the effects of stress factors (e.g., wind-throws, fires, industrial pollution) and those of the forest management practices and climatic changes. Furthermore, the use of soil biochemical indicators could be helpful in forecasting forest development. Ongoing studies on the soil enzymatic activity will allow for continuous evaluation of gradual changes in the soil biochemical properties in the hurricane- affected forest areas.

5. Conclusions

Enzyme activities were strongly associated with the contents of the organic matter in the soil, as evidenced by higher enzymatic activity in the organic horizon than that in the humus horizon of all the tested soils.

In naturally regenerating forest areas, the urease and dehydrogenase activities were higher in the year 2013 than in 2005, which can indicate a improvement of site conditions.

The obtained values of the soil biochemical parameters were strongly dependent on the forest regeneration methods – artificial reforestation had more beneficial effect on the regeneration rate of forest soil than on the natural regeneration.

The changes in soil enzymatic activity were correlated with both stand damage extent and the type of forest management applied after the hurricane.

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