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Effect of scots pine forest management on soil properties and carabid beetle occurrence under post-fire environmental conditions - a case study from Central Europe

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Abstract

Background: Fires have a fundamental impact on phytocoenoses and, depending on the size of the fire, can have a positive or negative effect. The role of fires in the formation of the species composition of plants, restoration of stands and changes in soil properties is well studied. However, the long-term relationship between forest management methods, soil properties and epigeic entomofauna assemblages in post-fire areas is still not clear. The effects of Scots pine stand management methods on biochemical soil properties and ground beetle assemblages in the largest post-fire area in Central Europe after the second World were investigated. The study was conducted in the Rudy Raciborskie Forest district in southern Poland. The soil properties and epigeic beetle community structure were analysed. The research covered areas with natural and artificial pine regeneration, which were subjected to various care treatments.

Results: The tendency for higher accumulations of organic matter in the soil of stands that underwent natural regeneration was proven. The stimulating role of soil organic carbon on the activity of dehydrogenases in the soil of naturally renewed areas with silvicultural treatment (NRAT) was noted. Regardless of the manner of stand regeneration, the activity of β-glucosidase was higher in the areas in which breeding treatments were practised. Furthermore, managed forest stands presented a higher abundance of carabid beetles than stands without treatment practices. Thirteen epigeic beetle species from the families Geotrupidae, Carabidae, Curculionidae, Cerambycidae and Silphidae were captured, with beetles from the first two families being the most numerous. Rare epigeal carabid species in the fauna of Poland and Europe, such as *Carabus glabratus* (Paykull) and *Carabus auronitens* Fabr., found appropriate habitat conditions for survival in the post-fire areas. Compared with the other areas, in the NRAT area, there were better stand and soil properties and more features conducive to epigeic entomofaunal occurrences. The highest post-fire content of polycyclic aromatic hydrocarbons was recorded in the soils of the sites that underwent artificial regeneration. The results suggest that preparing the soil before the introduction of new vegetation affects the amount of aromatic hydrocarbons (PAHs).

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Conclusions: The better performance of the NRAT stand draws attention to the positive aspects of the use of natural regeneration, both from ecological and economic perspectives. The effects of forest management on the amount of soil organic matter after fires have been proven. The natural regeneration of stands was conducive to the accumulation of organic matter. The enzymatic activity of soils is influenced by the renewal method and forest management strategy. The NRAT area was characterized by the highest number of carabid species.

Keywords: Stand treatment strategy, Forest regeneration, Enzyme activity, Soil organic carbon, Epigeic beetle assemblage structure

Background

Poland is situated in the area of *Europe* that is endangered by forest fires, which are primarily connected with its geographic location between the contrasting oceanic and continental climates (Kundzewicz and Matczak 2012). It is also characterized by permanent factors influencing the water balance, such as precipitation and cyclical long-term droughts, leading to reductions in groundwater (Kubicz et al. 2019). The fully biocenotic conditions of the forests and their uniform age and species structure make them particularly vulnerable to fires (Ubysz et al. 2006; Szczygieł 2012). According to the European Forest Fire Information System, Poland ranks third (after Portugal and Spain) in the average annual number of fires and eighth in the area covered by fires (Szczygieł 2012). The role of fires in the formation of the species composition of woody plants, restoration of stands and changes in soil properties have been widely studied (Martìnez-Sánchez et al. 1999; González-Pérez et al. 2004; Certini 2005; Knicker 2007; Homann et al. 2011; Verma and Jayakumar 2012; Barros et al. 2018; Stoddard et al. 2018). Many studies have also demonstrated either the negative or the positive effects of forest fires on carabid beetle assemblages (Holliday 1991; Beaudry et al. 1997; Wikars 1997; Gongalsky et al. 2006) and their biomass (Skłodowski 1994). Carabid beetles can play an important role as bioindicators of ecological soil productivity and disturbance in forest biocenoses because their biomass is strongly and positively related to the biomass of the macrofauna responsible for litter decomposition (Koivula 2011). Nevertheless, this phenomenon is usually analysed in the time soon after disturbances. Most often, after a fire, there is a temporary increase in soil fertility; however, after a few years, most of the nutrients available to the plants released from the fire are washed out, and ultimately, the fire contributes to the sterilization of the soil (Pritchett and Fisher 1987; Brais et al. 2000). After fires, the biological activity of soil decreases (Xue et al. 2014); in extreme cases, forest fires can lead to soil sterilization (Certini 2005). The reconstitution of microbial communities in forest soils after fires is a long-term process and depends to a great extent on the post-fire management strategy (Hawryś et al. 1998; Kazakevič et al. 1998). The method of post-fire treatment indirectly influences the shaping of the physical, chemical and biochemical soil properties (DeBano et al. 1998; Kaczmarek et al. 2004; Dziadowiec 2010; Gonet 2010; Francos et al. 2018). The effects of forest management practices on the composition of ground-dwelling beetle communities has also been reported (Lange et al. 2014; Skłodowski et al. 2018).

A forest fire in the Rudy Raciborskie, Rudziniec and Kędzierzyn Forest Districts in southern Poland was the largest fire in post-war Europe (FAO 1998; Piwnicki and Ubysz 2004). As a result of the fire, which occurred in 1992, the forests covering an area of approximately 10 thousand hectares were destroyed. The aim of this study was to evaluate the effect of forest management practices on epigeic entomofauna assemblages and the biochemical properties of post-fire soils 23 years after this event. The research included areas with natural and artificial Scots pine regeneration, which were subjected to various silvicultural treatments. From the perspective of post-fire economic and ecological measures, this issue is particularly important for the regeneration of productivity and biological diversity of habitats. The following hypotheses were tested: 1) the method of stand renewal and subsequent treatments carried out in pine stands determine the soil conditions, which consequently results in differences in the accumulation of soil organic matter and enzymatic activity; 2) in the post-fire stands that underwent natural regeneration without treatment, the abundance of ground beetle species reaches higher values than it does in the managed stands; and 3) the amount of polycyclic aromatic hydrocarbons in the soil is linked to the forest management strategy.

Materials and methods

Study area and experimental design

The study was conducted in the Rudy Raciborskie Forest district in southern Poland (50°13′44.2″ N, 18°27′ 20.0″ E) (Fig. 1). The mean air temperature in the studied plot is 8.5 °C, the vegetation growth period lasts from 220 to 230 days, and the annual rainfall is

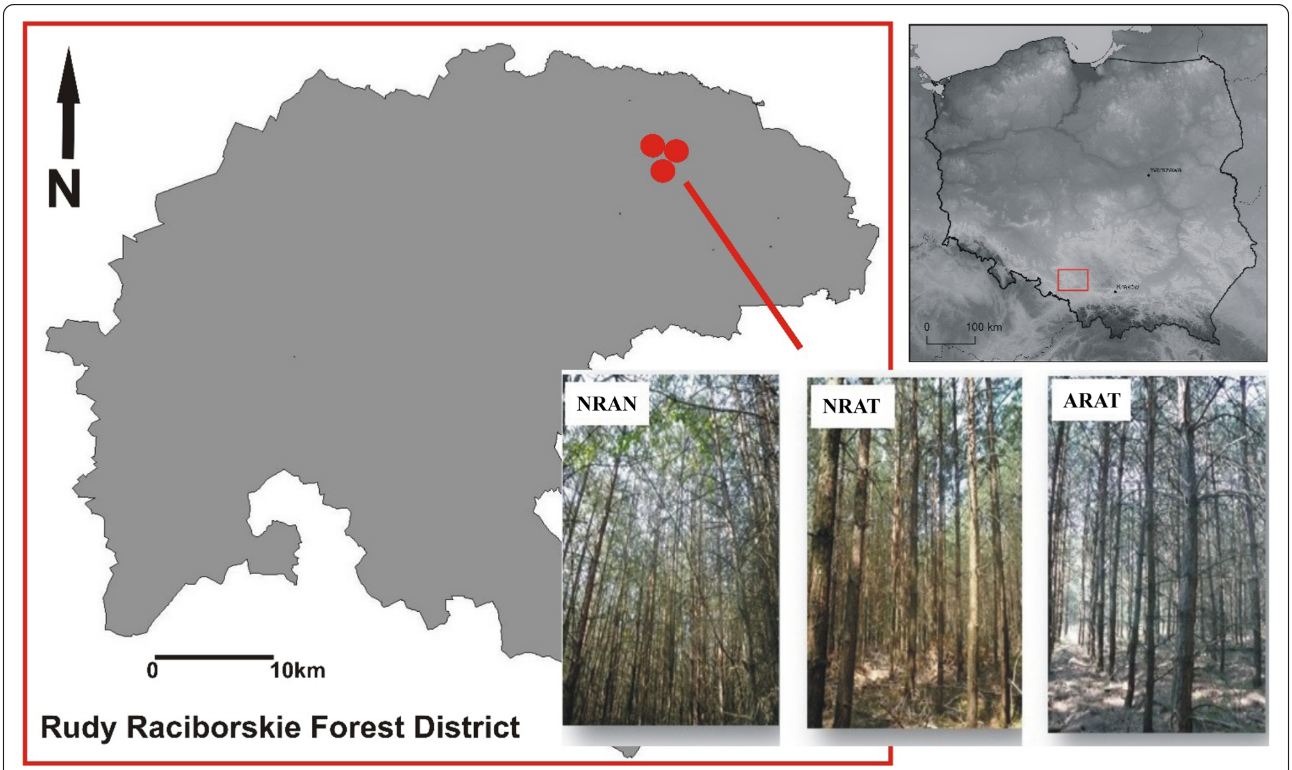

Fig. 1 Study plots sampling design in varius silvicultural treatments

approximately 630–650 mm (Operat siedliskowy dla Nadleśnictwa Rudy Raciborskie 2005). Podzols were predominant in the study area, constituting approximately 90% of the soil surface, while cambisols with brunic arenosols accounted for 10%. The dominant species is Scots pine, which occupies approximately 75% of the forest area (Operat siedliskowy dla Nadleśnictwa Rudy Raciborskie 2005). In the first half of June 2015, three 22-year-old *P. sylvestris* stands were selected for study. In each forest stand, 10 circular study plots with radii of 5.64 m and an area of 1 acre were established (in total, the tests were carried out at 30 study areas). The first group of study plots represented pine stands originating from natural regeneration with no previously performed silvicultural treatment (naturally renewed area with no treatment-NRAN). The second group of study plots represented pine stands originating from natural regeneration in an area where early and late clearings were performed in 2006 and 2015 (naturally renewed area with treatment-NRAT). In the third group of study plots, after burning, the stand was artificially regenerated with ploughed furrows for soil cultivation. In this stand, early and late clearings were carried out in two sequences, i.e., in 2007 and 2014 (artificial renewed area with treatment-ARAT). The research plots were established in areas dominated by *Leucobryo-Pinetum* communities. *Vaccinium myrtillus*, *Deschampsia flexuosa*, *Dryopteris carthusiana*, *Pleurozium schreberi*, *Dicranum undulatum* and *Leucobryum glaucum* were the dominant species in the undergrowth.

Measurements of stand biometric parameters

A complete inventory of all the living trees was conducted on each study plot. For each tree, the diameter at breast height (dbh) was measured with an accuracy of 0.5 cm. The height (H) of 30 randomly selected trees was evaluated with an accuracy of 0.1 m. On the basis of the measured dbh for each tree, the basal area (G) was calculated. To obtain the heights of all the tested trees, a tree height model was prepared for each study area of the stand. Based on the data collected from the particular study areas of the stand ($n = 300$ for each study area), height curves were created. Using the logarithmic function of the trend line, the heights of all the remaining trees within the study area were calculated. The volume of the trees that exceeded the threshold dbh measurement (7 cm) was established based on Scots pine timber volume tables for standing trees (Ochał 1999). Then, the stand form factor (f) was expressed as the ratio of the tree thickness to the basal area of the trunk, and the height of the tree was determined. Finally, for each study area, a stand form factor model was created, enabling the use of the polynomial function of the trend line, and the index value for the rest of the trees was determined. With the stand form factor, the thickness of the remaining trees was calculated. The slenderness coefficient (*S*) of the trees was calculated as the ratio of the height to the dbh.

Soil sampling and analysis

The test area covered by the soil sampling was dominated by Haplic Podzols. Soil samples for laboratory analysis were collected from the surface horizons, from a depth of 0–15 cm (Fig. 2), after removing the organic layers. From each group of study plots, 10 soil samples were taken for laboratory analysis, and each sample was a mixture of 5 replicates. The texture was determined using laser diffraction (Analysette 22, Fritsch, Idar-Oberstein, Germany), the pH was analysed using the potentiometric method, and the total nitrogen (N) and organic carbon (C_t) contents were measured using a Leco CNS True Mac Analyser (Leco, St. Joseph, MI, USA). The exchangeable aluminium (Al) was determined by the Sokołow method, and hydrolytic acidity was determined by the Kappen method. The concentration of cations was determined by ICP (ICP-OES Thermo iCAP 6500 DUO, Thermo Fisher Scientific, Cambridge, U.K.). Using Lenhard's method based on Casida's procedure, dehydrogenase activity (DH) was determined (Alef and Nannipieri 1995). To determine the activity of β-glucosidase (BG), the method of Eivazi and Tabatabai (1990) was used. The PAHs were analysed with the HPLC method (Błońska et al. 2016a).

Fig. 2 Soil sampling and trap scheme

Epigeic beetle control and community structure analysis

The occurrence of ground beetles was monitored from 30 June to 1 October 2015 using Barber pitfall traps (9 cm in diameter and 0.5 L capacity; Fig. 2) containing a fluid preservative (ethylene glycol). In each type of study site, five individual pitfall traps were located in every second trial plot and were placed near a tube that snapped into the centre of the plot surface. The traps were dug into the ground to a depth that allowed the upper edge of the container to rest at ground level. Insect control was carried out at biweekly intervals. The beetle specimens collected from the traps were identified to the species level with the keys from Trautner and Geigenmüller (1987), Hůrka (1996) and Klausnitzer (2005). The beetle assemblages were analysed using individual dominance indices to reflect the percentage of particular beetle species in the pool of all the insects collected at a given study site. To compare the forest biocenoses, the Simpson dominance index (*c*) (Simpson 1949), the Shannon-Wiener diversity index (H') (Shannon and Weaver 1948) and the Simpson diversity index (*D*) (Simpson 1949) were used. Moreover, for carabid beetles, ecological features (Burakowski et al. 1974; Hůrka 1996) were determined. We divided the beetles into 1) trophic groups: large zoophages with a body length above 15 mm, small zoophages with a body length below 15 mm and hemizoophages (omnivorous species); 2) ecological groups: forest, eurytopic and open areas species; and 3) geographical groups: palearctic, holarctic and European species (Skłodowski and Garbalińska 2007).

Based on carabid humidity preferences, we distinguished 1) hygrophilous species, whose occurrence is related to the proximity of water, 2) mesophilic species, which are typical of areas presenting moderate soil moisture, and 3) xerophilic species, which are characterized by low water requirements. The scientific names of the insects were assigned according to de Jong et al. (2014).

Statistical analysis

One-way analysis of variance (ANOVA) was used to compare characteristics between the different forest management areas. The results of the ANOVA were assessed with a Shapiro-Wilk's normality test, Bartlett's test of homogeneity of variances and Fligner-Killeen's test of homogeneity of variances. Tukey's HSD multiple comparison tests were used in the post hoc analysis. The effect of forest management practices and the type of regeneration on epigeic beetle abundance was analysed using a Mann-Whitney U test. Principal component analysis (PCA) was used to evaluate the relationships between the chemical properties, enzymatic activity of the soil and type of forest management. The effects of soil properties and forest management on enzyme activity was analysed by a generalized linear model (GLM). The statistical significance of the results was verified at the $\alpha = 0.05$ significance level. All the necessary analyses were performed in the R programming language (version 3.3.3), R studio (version 1.0.136) (R Development Core Team 2017) and (Statistica 10 software 2010).

Results

Characterization of the stands

The biometric parameters of the studied stands under the examined management techniques differed significantly. The pine trees in the NRAT area were characterized by the highest dbh (10.76 cm) and volume (0.0494 m^3), while the trees in the NRAN area were characterized by the lowest dbh (4.29 cm) and volume (0.0027 m^3). Statistically significant differences in the slenderness coefficient between management techniques were also observed. The trees in the NRAN area were characterized by a higher ratio of slenderness, nearly 41% and 45% higher than those in the NRAT and ARAT areas, respectively (Table 1). The most distinguishing differences between the analysed stand characteristics were observed between the ARAT and NRAN areas (Table 2).

Table 2 Results of one-way analysis of variance (ANOVA) and Tukey's HSD test for the relation between study plots and growth parameters of the stand

Variant of area management	*P* value			
	V	dbh	*H*	*S*
NRAT- NRAN	**0.0000**	**0.0000**	0.3053	**0.0000**
ARAT-NRAN	**0.0000**	**0.0000**	**0.0024**	**0.0000**
ARAT-NRAT	**0.0034**	**0.0401**	0.1612	**0.0430**

Values in bold are statistically different ($p < 0.05$), volume (V, m^3); diameter at breast height (dbh, cm); Lorey height (H, m); slenderness coefficient (S)

Soil properties

In the studied soils, the sand fraction was dominant; its content varied from 88% to 99% depending on the study area. A small amount of silt and clay was present. There were no statistically significant differences in texture among the selected study areas (Table 3). The highest average organic carbon (5.17%) and nitrogen (0.25%) contents were recorded in the soil of the NRAT area (Table 3). The lowest contents of carbon (3.86%) and nitrogen (0.19%) were found in the soil of the ARAT area (Table 3). There were no statistically significant differences in the carbon content between the study areas. The soil of each study area was characterized by similar organic matter decomposition rates, expressed as the C/N ratio. A lower pH was noted in the soils of the NRAT area than in the soils of the other study areas (Table 3). There were no statistically significant differences in the base cation content (BC) between the study areas. The β-glucosidase and dehydrogenase activity varied among the soils of the study areas. The β-glucosidase activity was significantly lower in the soils of the NRAN area than in the soils of the ARAT and NRAT areas (Table 3). No statistically significant differences were found in the dehydrogenase activity of the soils from all the areas sampled.

The highest PAH concentration was recorded in the soils of the post-fire study area with artificial regeneration after soil preparation (Table 4). In the soils of this study area, 3-, 5- and 6-ring PAHs were recorded. The

Table 1 The mean (± SD) values of examined features of trees in Scots pine stands in the study plots

Variant of the area management	N (pcs·ha^{-1})	Diameter at breast height (cm)	Lorey height (m)	Basal area[a] (m^2·ha^{-1})	Volume (m^3) Total volume[a] (m^3·ha^{-1})	Slenderness coefficient
NRAN	21,440	4.29[a] ± 2.06	7.70[a]	39.43[a]	0.0027[a]	203.62[a]
					58.93	
ARAT	3950	9.73[b] ± 3.31	10.03[b]	32.76[b]	0.0346[b]	112.31[b]
					136.73	
NRAT	3010	10.76[b] ± 2.38	12.51[c]	28.71[b]	0.0494[b]	120.72[b]
					148.76	

[a]The total volume (Vc) expressed as a volume sum of all trees at 10 circular trial plots per 1 ha, different small letters in the upper index of the mean values mean significant differences

Table 3 Mean values and range of properties in soil of different study plots

Characteristics of soil	NRAN			ARAT			NRAT		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Ct	4.83[a]	3.00	6.41	3.86[a]	1.71	8.38	5.17[a]	2.34	7.80
Nt	0.23[a]	0.12	0.31	0.19[a]	0.08	0.39	0.25[a]	0.08	0.48
C/N	21.43[a]	16.93	30.01	21.98[a]	14.37	27.64	22.86[a]	16.35	42.97
pH H_2O	4.02[a]	3.78	4.35	4.24[a]	3.98	4.87	3.98[b]	3.73	4.40
pH KCl	3.20[a]	2.98	3.50	3.38[a]	3.14	3.79	3.17[b]	2.84	3.61
Y	17.53[a]	8.42	23.45	13.16[a]	6.78	24.62	17.34[a]	9.61	26.40
Al	5.48[ab]	3.06	7.09	4.14[b]	1.37	8.47	6.62[a]	3.75	8.51
Ca	0.40[a]	0.09	0.63	0.52[a]	0.19	1.50	0.31[a]	0.11	0.56
K	0.19[a]	0.06	0.34	0.09[b]	0.05	0.19	0.12[ab]	0.09	0.15
Mg	0.10[a]	0.03	0.17	0.06[b]	0.04	0.11	0.05[b]	0.04	0.07
Na	0.007[a]	0.002	0.014	0.007[a]	0.004	0.010	0.007[a]	0.004	0.011
P	60.08[a]	26.88	107.10	31.91[a]	6.79	81.20	38.32[a]	7.07	93.10
BC	0.70[a]	0.19	1.10	0.68[a]	0.29	1.62	0.49[a]	0.27	0.76
Sand	95[a]	90	98	96[a]	92	99	94[a]	92	95
Silt	4[a]	2	8	3[a]	1	6	5[a]	4	6
Clay	1[a]	0	2	1[a]	0	3	1[a]	0	1
DH	14.88[a]	2.37	28.12	11.69[a]	3.20	20.15	9.44[a]	2.95	13.45
BG	110.03[b]	54.52	161.25	309.97[a]	99.67	715.19	309.04[a]	140.66	592.76

Ct: carbon content (%); N: nitrogen content (%); Y: hydrolytic acidity (cmol(+)·kg^{-1}); Al: exchangeable aluminium (cmol(+)·kg^{-1}); Ca^{2+}, K^+, Mg^{2+}, Na^+ content (cmol(+)·kg^{-1}); P content (mg·kg^{-1}); BC: base cations (cmol(+)·kg^{-1}); sand, silt and clay content (%); DH: dehydrogenase activity (μmol TPF·kg^{-1}·h^{-1}), BG: β-glucosidase activity (mmol pNP·kg^{-1}·h^{-1}), different small letters in the upper index of the mean values mean significant differences

total concentration of PAHs in the soils of this study area was 4.923 μg·kg^{-1}. The highest concentrations were recorded for indene (1,2,3-c,d) pyrene and benzo (g,h,i) perylene and benzo (b) fluoranthene, and their contents were 1225, 1231 and 1066 μg·kg^{-1}, respectively. The soils of the other study areas were characterized by lower PAH contents. In the soils with natural regeneration, only fluorene, phenanthrene and benzo (a) anthracene were present. The total concentration of PAHs in the soils of the NRAN area was 0.784 μg·kg^{-1}, and in the soils of the NRAT area, the total PAH concentration was 0.462 μg·kg^{-1} (Table 4).

The PCA confirmed the stimulating effect of carbon and nitrogen content on the enzymatic activity (Fig. 3). The two main factors had a significant impact (54.31%) on the variance of the variables. Factor 1 relates to the carbon and nitrogen content. In factor 2, the factors that explain the most variation are associated with the forest management strategy. The soils of the ARAT area were associated with the highest pH and a relatively low carbon and nitrogen content. The soils of the NRAN area contained the most base cations. Based on the GLM analysis, a strong dependence of the enzymatic activity on the carbon content in the soils was observed (Table 5).

Ground entomofauna assemblages

During the field study, in the three stands subjected to various treatments, a total of 2573 specimens of ground beetles, representing 5 families, were found. Regardless of the study site type, *Anoplotrupes stercorosus* Scriba and *Trypocopris vernalis* (L.) were the most numerous insect species, together accounting for 72.5% and 75.7%

Table 4 Polycyclic aromatic hydrocarbons (μg·kg^{-1}) in soil of different study plots

Variant of the area management	Acy	Flu	Phe	Flt	Pyr	BaA	Chr	BkF	BbF	BaP	IcdP	BghiP	ΣPAHs
NRAN	n.d.	n.d.	0.289	n.d.	n.d.	0.495	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.784
ARAT	0.053	n.d.	0.247	n.d.	n.d.	n.d.	n.d.	0.444	1.066	0.657	1.225	1.231	4.923
NRAT	n.d.	0.173	0.298	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.462

acenaphtylen (Acy), fluoren (Flu), phenanthrene (Phe), fluoranthene (Flt), pyrene (Pyr), benzo(a) anthracene (BaA), chrysene (Chr), benzo(k), fluoranthene (BkF), benzo(b) fluoranthene (BbF), benzo(a) pyrene (BaP), indeno (1,2,3-c,d) pyren (IcdP), and benzo(g,h,i) perylene (BghiP); n.d. – no determined

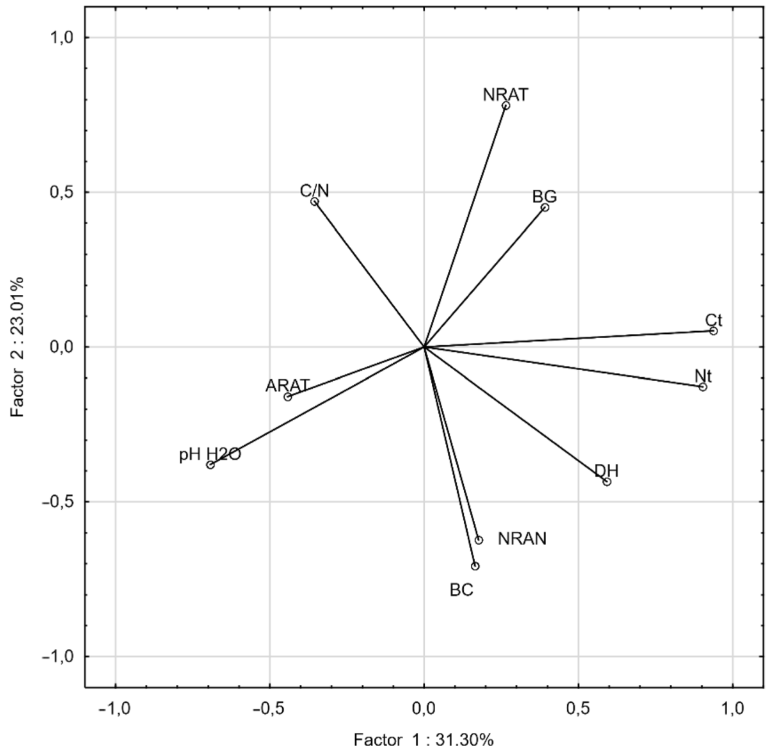

Fig. 3 Projection of the variables on the factor plane in the soil of the different study plots

of the total insect specimens caught in the NRAN and NRAT areas, respectively. Seven carabid species composed the second most numerous group of ground beetles found at the study sites. A higher abundance of carabids was observed in the ARAT and NRAT areas, constituting 21.2% and 21.9% of the total number of insect specimens caught, respectively, whereas in the NRAN areas, the share of carabid beetles reached a value of less than 15.0%. Forest species classified as large zoophages and with broad distributions were dominant. Species with moderate humidity requirements and those that prefer moisture-rich habitats were similarly numerous. At each study site, the most numerous carabids were *Carabus violaceus* (L.) and *Pterostichus niger* Shaller. Among the captured carabid beetles, *C. auronitens* Fabr. and *C. glabratus* Paykull have special protection status in Poland. Interestingly, similarly low values for

Table 5 Summary of GLM analysis of the effect of the soil properties and forest management type on the enzyme activity

Effect	DH		BG	
	F	*P* value	*F*	*P* value
Forest management	1.50	0.2424	0.03	0.9708
Ct	**18.19**	**0.0002**	**11.62**	**0.0023**
Forest management × Ct	2.58	0.0962	1.04	0.3665

Ct: carbon content; DH: dehydrogenase activity; BG β-glucosidase activity

insect species richness and diversity were found in all the study site types (Table 6).

It was proven that the type of forest regeneration did not significantly influence the epigeic beetle specimens caught in the traps (Mann-Whitney U test: $Z = 1.89$; $p = 0.0576$). Moreover, a significant difference was found in the number of insect specimens between the managed and unmanaged stands, with the number of insect specimens in the managed stands two and a half times higher than that in the unmanaged study sites (Mann-Whitney U test: $Z = 4.56$; $p = 0.0000$). When analysing the carabid specimens, statistically significant effects of the type of regeneration (Mann-Whitney U test: $Z = 6.08$; $p = 0.0000$) and management method (Mann-Whitney U test: $Z = 5.09$; $p = 0.0000$) on abundance were found.

Discussion

The effect of forest management on the amount of soil organic matter in soils after fires has been proven. Natural stand regeneration was conducive to the accumulation of organic matter. According to Schmidt et al. (1996), intensive soil preparation results in extensive disturbances, which translate into changes in soils, including changes in the amount of soil organic matter. Knicker (2007) and Terefe et al. (2008) claim that changes in the composition and amount of soil organic matter are two of the most common consequences of

Table 6 Dominance structure, beetles' assemblage indices and the characteristics of Carabids species

Families/Species	Ecological features				Variant of the area management		
	A	B	C	D	NRAN	ARAT	NRAT
Carabidae					14.8	21.2	21.9
Carabus auronitens Fabr., 1792[R]	HZ	F	PA	mez	0.5	0.3	0.4
Carabus arcensis Herbst, 1784	LZ	F	EU	mez	0.2	0.1	0.1
Carabus violaceus L., 1758	LZ	E	PA	hig	6.8	8.8	9.6
Carabus glabratus Paykull, 1790[R]	HZ	F	HA	hig	0.1	2.0	–
Carabus hortensis	LZ	F	PA	mez	0.2	0.1	–
Pterostichus niger Shaller, 1783	LZ	F	PA	hig	6.3	9.5	10.6
Harpalus rufipes De Geer, 1774	HZ	O	PA	xer	0.9	0.4	1.2
Geotrupidae					72.5	73.7	75.7
Anoplotrupes stercorosus Scriba, 1791					49.2	47.7	49.4
Trypocopris vernalis L., 1758					23.3	26.0	26.3
Silphidae					0.9	2.0	1.2
Nicrophorus vespilloides Herbst, 1783					0.9	2.0	1.2
Cerambycidae					–	–	0.1
Stictoleptura rubra					–	–	0.1
Curculionidae					12.0	2.9	0.8
Pissodes pini L., 1758					6.3	1.0	0.2
Hylobius abietis L., 1758					5.7	1.9	0.6
Number of individuals (pcs.)					636	692	1245
Number of species (pcs.)					12	12	11
Abundance (%)					24.7	26.9	48.4
Simpson domination (c)					0.311	0.312	0.333
Species diversity of Shannon Weaver (*H'*)					2.170	2.135	1.972
Simpson's species richness (*D*)					0.687	0.686	0.666

The superscript "R": rare species included in the Polish Red Data Book of Animals (Głowaciński and Nowacki 2002)
Ecological features: A: trophic group (large zoophages: LZ; small zoophages: SZ; hemizoophages: HZ); B: ecological group (forest species: F; eurytopic species: E; species of open areas: O); C: geographical group (Palaearctic species: PA; Holarctic species: HA; European species: EU); D: environmental humidity preferences (hygrophilous species: hig; mesophilic species: mez; xerophilic species: xer.)

fires. In our research, a significant share of carbon in the surface soil horizons was noted, which indicates the restoration of the humus horizon. During forest fires, temperatures range from 200 to 300 °C. Soil organic matter oxidizes at a temperature of 200 °C to 315 °C (Knicker 2007), whereas lignin and hemicellulose degrade at a temperature of 130 °C to 190 °C (Chandler et al. 1983). The loss of organic matter as a result of a fire in light soils significantly worsens their sorption ability (Januszek et al. 2001). The nutrients collected in the ash, resulting in a reduced sorption capacity, are quickly exhausted or eluted due to wind or water erosion. The availability of nutrients after a fire is generally higher due to the combustion of organic matter in the soil. In the soils of the post-fire area, regardless of the forest management method, the content of base cations was low. The low content of base cations is a result of elution, which is facilitated by the sandy grains of the soils examined.

To evaluate the microbial activity, the dehydrogenase and β-glucosidase activities in the soils were investigated. Soil enzyme activities are used as indicators of changes due to their sensitivity to environmental perturbation (Błońska et al. 2017). Dehydrogenase is the most important soil enzyme and is frequently used in determining the influence of various factors on the microbiological quality of soils (Błońska et al. 2016b). In our study, a stimulating role of carbon on the activity of dehydrogenases in the soil was found. The PCA confirmed the positive relationship between dehydrogenase activity and carbon content. Using the GLM, a strong dependence of the enzymatic activity on the soil organic carbon content was observed. Soil enzymes play an important role in the decomposition of organic matter (Aon and Colaneri 2001; Sinsabaugh et al. 2008). Soil microorganisms and their enzymes participate in all the processes associated with the transformation of organic matter in the soil. The results also showed that, regardless of the method of stand regeneration, the activity of β-glucosidase was higher in the post-fire areas with treatment. The breeding treatments may have improved the predominant thermal conditions in the stand as well as the soil cover. The stand in the NRAN area, which was not subjected to any management, was significantly different in terms of structure and characteristics from the remaining stands, which had been treated in the past. According to Wallenstein et al. (2009), temperature and humidity are the basic parameters affecting the enzymatic activity of soils. Variability in β-glucosidase activity associated with humidity and temperature was noted by Steinweg et al. (2012).

Low levels of polycyclic aromatic hydrocarbons were recorded 23 years after the fire. The sum of the PAHs in the soils of the study areas did not exceed 100 μg·kg^{-1}. The threshold values of classification according to Maliszewska-Kordybach (1996) were 200, 600, and 1000 μg·kg^{-1}. The studied soils were dominated by the sand fraction, which is not conducive to PAH accumulation. According to Lu et al. (2012), the highest PAH concentration was associated with clay and decreased in the following order: clay > silt > coarse sand > fine sand. The highest content of polycyclic aromatic hydrocarbons was recorded in the soils of the post-fire areas with artificial regeneration. In these soils, five- and six-ring hydrocarbons dominated. These results suggest that the method of preparing the soil before the introduction of new vegetation affects the amount of PAHs.

The forest management strategy also has a significant impact on the epigeic entomofaunal community structure. The highest abundance of captured beetles was found in NRAT and ARAT areas. The managed stands were also characterized by higher predatory carabid abundance in comparison to that in the unmanaged stands, which developed from natural regeneration. As carabid beetles play a crucial role in evaluating the development of forest biocoenoses, we concluded that there were more favourable conditions for tree growth in the treated stands. This seems to confirm the results of the soil analyses and the characteristics of the examined stands. We found that the stand in the NRAN area, which, in its history, has not been subjected to any treatments, significantly and negatively differs in terms of structure relative to the other examined stands and the managed forest model.

The dbh parameter was characterized by a large variation; in the NRAN area, the dbh values were less than half as much as those in the NRAT and ARAT areas. Such a weak increase in tree thickness is caused by a high density during the time when the trees undergo the greatest increase in thickness (Jaworski 2013). A similar pattern was observed for stand height, with the tallest tree predominating the NRAT area, slightly lower trees occurring in the ARAT area, and the shortest trees occurring in the NRAN area. Consequently, the total volume of the stand representing the NRAN area was almost three times lower than that of the stand in the NRAT area, which was characterized by the largest total volume among the examined stands. This phenomenon is undoubtedly related to the difficult growth conditions for the trees in the stands that had not been managed in the past; these growth conditions led to a significant intensification in the trees' inter-individual competition for light, water and nutrients (González de Andrés et al. 2018).

The degree of tree density, regulated by cultivation cuts, directly affects the value of tree growth; achieving maximum growth is possible with the optimal number of trees. Generally, the value of individual trees increases as their density decreases; however, by removing trees, the average growth of the stand decreases (Šmelko et al. 1992). In our study, the stand in the NRAN area was characterized by the highest stand density, a minor increase in the thickness of the trees and the largest number of dying trees in comparison with the stands originating from natural and artificial regeneration. These properties may indicate that the maximum density was reached in the stands in the NRAN area, while the optimal density was reached in the stands in the NRAT and ARAT areas (Bruchwald 1988). Moreover, the high density of trees on the surface of the NRAN stand had a negative impact on the slenderness ratio of the trees, determining their low stability and resistance to abiotic damage. Generally, the larger the growth space, the greater the increase in thickness in relation to the height of a tree, which results in a decrease in the slenderness factor and an increase in stand stability (Baldwin et al. 2000; Kantola and Mäkelä 2004; del Río et al. 2017). Moreover, the initial plant density is crucial for the mean slenderness of trees (Pretzsch and Rai 2016). The value of the slenderness coefficient was relatively low (above 100) for all the study areas, indicating the low stability of the examined stands (Jaworski 2013). However, it is normal for the value of the slenderness factor to exceed 100 in such young stands. In the stand in the NRAN area, where the slenderness factor was 201, there is extremely low stand stability, which is associated with a very high threat from strong winds and snowfall.

Stand structure parameters have indirect impacts on the ground beetle community. Lange et al. (2014) found a higher number of Carabidae and Staphylinidae ground-dwelling beetle species as well as a higher insects species richness in managed stands relative to that in unmanaged forests. The authors explain this pattern by the higher diversity of vegetation and microhabitat conditions in stands with smaller canopies. Furthermore, the authors note that the stand features do not fully explain this phenomenon. Other features, such as soil moisture parameters, should also be taken into account. A negative impact of crown cover on Carabidae diversity and a positive effect of forest management through canopy gap creation were also found by Spake et al. (2016). Jukes et al. (2001) proved that there were negative carabid species richness and diversity relationships with canopy vertical structure and soil organic matter. Surprisingly, we did not confirm this pattern, as the managed and unmanaged stands presented similarly low species richness and diversity. These contrasting results might have consequences at the regional level in our study (Fuller et al. 2008). Many ground-dwelling species are characterized by different regional habitat preferences (Gossner et al. 2014); thus, studies in different regions make it difficult to draw clear conclusions about forest management strategy impacts (Koivula 2012). Nevertheless, the NRAT stand, characterized by the highest tree height and diameter among all the analysed stand types, presented the highest number of insects overall and carabid species. Barkley et al. (2016) confirmed a strong dependence of the carabid community on stem diameter, reporting carabid specimens more frequent from stands with high tree canopy heights, large trees and high vertical foliage complexity.

Based on the obtained results, the natural regeneration of forests with management practices is considered the best reforestation method, since it creates the ideal conditions for the natural processes occurring in forest ecosystems.

Conclusions

Our findings underline the importance of a multifactorial approach to understanding the process of restoring forest ecosystems after wildfires. The field experiments provided evidence that forest management influences soil properties to a small extent, while having an important impact on ground beetle communities. As expected, the enzymatic activity of soils was affected by the renewal method and forest management strategy. The results suggest that the method of preparing the soil before the introduction of new vegetation affects the carbon content in the soil. The better performance of the stand in the NRAT area indicates the positive influence of natural regeneration from an ecological and economic point of view. Further studies are needed to monitor soil changes during the restoration process. Considering the characteristics of the soils, the value of human intervention in natural regeneration processes has not been proven. Nevertheless, bearing in mind the strong effect of forest management type on forest structure and epigeic beetle assemblages, intervention in the natural regeneration processes of pioneer species growing in post-fire areas may be considered appropriate human action. Forests are increasingly affected by climate change and are thus vulnerable to fires. The obtained results suggest that natural regeneration with management practices is the most reasonable method for managing forests after fires. This method for managing forest areas ensures the maintenance of correct soil conditions and the biodiversity of the forest ecosystem.

Abbreviations

ARAT: Artificial Renewed Area with Treatment; BG: β-glucosidase activity; dbh: the diameter at breast height; DH: Dehydrogenase activity; E: Eurytopic species; EU: European species; F: Forest species; G: Stand basal area; H: Lorey height; H/D: Slenderness coefficient; HA: Holarctic species; Hig: Hygrophilous species; HZ: Hemizoophages; LZ: Large zoophages; Mez: Mesophilic species; N: Number of trees per hectare; NRAN: Natural Renewed Area with No treatment; NRAT: Natural Renewed Area with Treatment; O: Species of open areas; PA: Palaerctic species; SZ: Small zoophages; V: Stand volume; Xer: Xerophilic species

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Authors' contributions

EB, BB designed the experiment and implemented the study, with assistance from MK and JL. All authors analysed the results and contributed to the manuscript writing and editing. All authors read and approved the final manuscript.

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Competing interests

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