Acta Agrobotanica

DOI: 10.5586/aa.1783

Publication history
Received: 2019-02-22
Accepted: 2019-07-25
Published: 2019-09-30

Handling editor
Piotr Sugier, Faculty of Biology and Biotechnology, Maria Curie-Skłodowska University in Lublin, Poland

Authors' contributions
RH: idea of the study, fieldwork, data analysis, writing the manuscript; AKB: data analysis, writing the manuscript

Funding
This research was financially supported by the Department of Botany and Nature Protection, Faculty of Biology and Environmental Protection, University of Silesia in Katowice, Poland.

Competing interests
No competing interests have been declared.

Citation
Hanczaruk R, Kompała-Bąba A. Effect of thermal activity on the differentiation of the vegetation of the "Ruda" postmining heap in Zabrze (Poland). Acta Agrobot. 2019;72(3):1783. https://doi.org/10.5586/aa.1783

ORIGINAL RESEARCH PAPER

Effect of thermal activity on the differentiation of the vegetation of the "Ruda" postmining heap in Zabrze (Poland)

Robert Hanczaruk*, Agnieszka Kompała-Bąba

Department of Botany and Nature Protection, Faculty of Biology and Environmental Protection, University of Silesia in Katowice, Jagiellońska 28, 40-032 Katowice, Poland

* Corresponding author. Email: roberthanczaruk@gmail.com

Abstract

This paper presents the results of a study on the vegetation of the thermally active postmining heap "Ruda" in Zabrze (Poland). The aims of the study were: (***i***) to show the differentiation of the vegetation that has developed as a result of the thermal activity, and (***ii***) to determine the effect of thermal activity of the spoil heap on species richness and species diversity of the vegetation. Twelve plant communities were recorded on the heap. Thermal activity has a statistically significant impact on species richness ($Z = 2.13$, $p = 0.03$) and species diversity ($Z = 2.29$, $p = 0.02$). The species composition of plant communities reflects the habitat conditions, which are conditioned by thermal activity. As the distance from a zone with increased thermal activity increases, the degree of the spontaneous succession of vegetation and the complexity of the vegetation increase. Moreover, the share of annual species and kenophytes decreases in favor of perennial plants and apophytes. The number of plant communities (from four to eight), their species richness (number of species from 15 to 22) and species diversity (Shannon–Wiener diversity index from 1.81 to 2.19) also increase. A DCA analysis showed an increase in the shading, humidity and pH of the substrate, and the thickness of the dead organic matter within the gradient of the thermal activity.

Keywords

development of plant cover; environmental stresses; environmental conditions; extreme habitats; postindustrial sites

Introduction

The intensive exploitation of hard coal since the eighteenth century has contributed to a strong transformation of the natural environment of the Upper Silesian Industrial Region in southwestern Poland [1]. It is estimated that approximately 400 kg of waste is created for each tonne of raw material that is extracted [2]. Until the end of the twentieth century, a significant part of this waste was deposited in the over-level dumps [3]. The high content of skeletal parts in the stored material can hinder the development of the spontaneous plant cover of postmining heaps. This facilitates aeration and may cause the oxidation of any combustible components that are contained in the waste (carbonaceous matter and pyrite) and, consequently, can lead to a self-heating and self-combustion of the fuel. The thermally active areas of heaps are usually devoid of plant cover [2,4].

The aims of this research were: (***i***) to show the differentiation of the vegetation that is occurring in the carboniferous gauge and that has developed as a result of the thermal activity, in the context of reclamation, and (***ii***) to determine the effect of the thermal activity of the spoil heap on the diversity of the vegetation.

Material and methods

Site description

The investigated dump, "Ruda", is located in Zabrze in the Upper Silesian Industrial Region of southwestern Poland on the Silesian Upland between 50°18′56″ latitude and 18°49′31″ longitude [5] (Fig. 1).

Between 1960–1997, 1.7 million tons of waste was deposited on the heap over an area of approximately 27 ha. A biological reclamation was carried out in 1989 which involved sowing grasses and legumes and also planting trees and shrubs (including *Acer* sp., *Betula pendula*, *Pinus sylvestris*, *Salix* spp.). Additionally, heathland was created in the northwest part of the heap. This part of the dumping ground was thermally active and the area of the fire zone is constantly growing. Extinguishing works were carried out in 2006–2011 but they were ineffective and expensive. Some other activities were undertaken in the second half of 2017 in the thermally active area of the heap. They involved the removal of vegetation and the selection of incoming material. The reclaimed area was then covered with loamy and sandy soils [6].

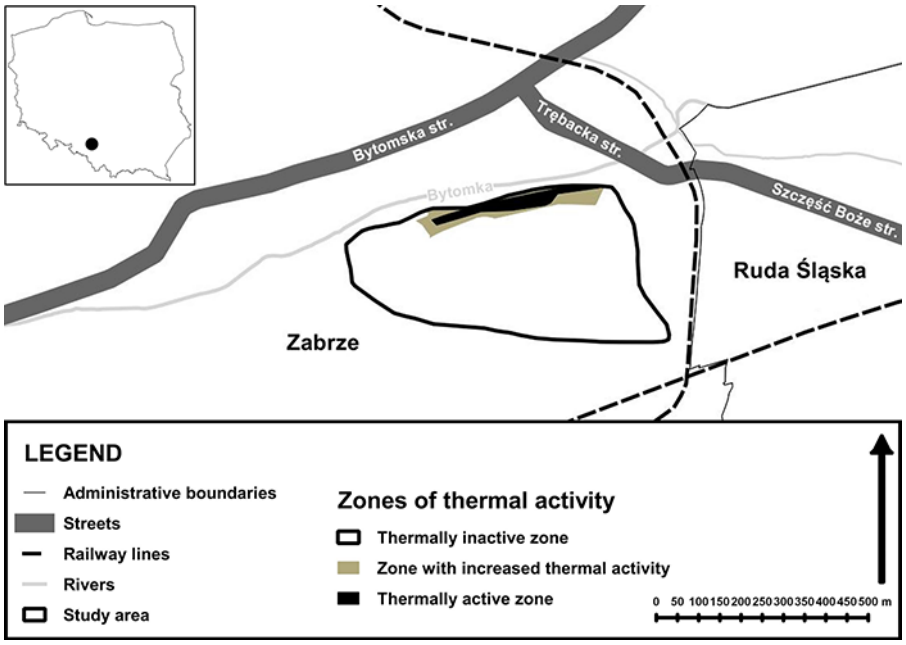

Fig. 1 Map of the thermal activity of the postmining "Ruda" heap.

Assessment of thermal activity

The substrate temperature was measured by noncontact infrared thermometry at depths of 0–10 cm in three repetitions in order to determine the thermal activity of the spoil heap. The state of the thermal processes on the heap was then evaluated using a methodology based on that prepared by Korski [7] and Wasilewski and Korski [8], and the approximate temperatures inside the heap were estimated.

Vegetation sampling

During the growing seasons of 2015–2017, 83 phytosociological relevés with a 25 to 100 m^2 surface area were made according to the Braun-Blanquet method [9]. The surface area for this phytosociological research was decided for the given type of plant community according to the guidelines adopted in the guide for phytosociological research [10]. On the other hand, within the given type of a community the area of the relevé was always the same. For each relevé, the cover and height (cm) of the tree, shrub, and herb layers

as well as the thickness of the dead organic matter were determined. The cover of the each layer was estimated as a percentage, whereas the height of the layer was determined using a measuring tape. In order to measure tree height a laser rangefinder was used. The thickness of the dead organic matter (cm) was calculated on the basis of the mean of five measurements made within each relevé [11].Additionally, the coordinates (latitude and longitude), slope, and inclination of the heap were determined using a GPS. The plant nomenclature follows the checklist given in Mirek et al. [12].

Data analysis

Before further analyses, the Braun-Blanquet scale used for vegetation sampling was transformed to percentage values according to the scale: r – 1%, + – 2%, 1 – 3%, 2 – 13%, 3 – 38%, 4 – 68%, 5 – 88% [13].

In order to assess the affinity of a particular species to a given vegetation unit, the fidelity concept was applied [14]. As a measure of fidelity, the phi coefficient of association (φ) was used and all values were multiplied by 100. Species with a phi ≥ 25 and with $p \leq 0.05$ based on the Fischer test were considered to be diagnostic species [13,15]. Moreover, species with a percentage cover ≥50% in at least in 25% of the relevés in a given type of community were considered to be the dominant species [15]. The species richness and Shannon–Wiener diversity index (H') were calculated using JUICE 7.0 software for the vegetation types that were distinguished [13].

Detrended correspondence analysis (DCA) was used to detect the main gradients that are responsible for the differentiation of the vegetation that occurs on the coal mine spoil heap. The mean Ellenberg indicator values (light, moisture, soil reaction, nutrients) that were calculated for the individual relevés and the temperature of the substrate, as well as the thickness of dead organic matter, were used as supplementary data in the DCA in order to interpret the ecological differences between the vegetation communities [16]. All of these analyses were performed in the CANOCO 5 package [17,18].

In order to determine the differences between the thermal activity zones that were distinguished in relation to species richness and diversity, the nonparametric Mann–Whitney U test was used with STATISTICA 13.1 software [19].

Results

Thermal activity zones

Based upon the assessment of the development of thermal processes on the heap, three zones were distinguished that were differentiated in terms of the thermal activity (Fig. 1, Tab. 1):

- A thermally inactive zone (I) which has an average substrate temperature of 25.4°C, and no signs of the development of an endogenic fire.
- A zone with increased thermal activity (II) which occurs on northwestern slopes of the coal mine spoil heap. The average temperature of the ground is 33.6°C. The "sweating of the material" has a characteristic sweetish smell of ethane and a slightly tarry odor and indicates that the oxidation of combustible components contained in the deposited waste is specific for this zone. The approximate temperature in the interior of the dump is 80–130°C.
- A thermally active zone (III) located on the northwestern slopes of the coal mine spoil heap. The average temperature of the substrate exceeds 60°C. Light-grey smoke and a noticeable tarry odor indicate a significant advancement of the thermal phenomena in this part of the dump and the possibility of spontaneous combustion of stored material. The approximate temperature inside the heap is around 300–370°C. This zone is devoid of vegetation due to extreme habitat conditions.

For further research, we took into account only the thermally inactive zone and a zone with increased thermal activity as the thermally active zone was devoid of vegetation.

Tab. 1 Zones of the thermal activity on the post-mining "Ruda" heap.

	Zones of thermal activity		
	Thermally inactive (I)	**With increased thermal activity (II)**	**Thermally active (III)**
Temperature (°C) of the substrate	25.42 ±2.30	33.64 ±2.14	60.20 ±10.82
Symptoms of the development of an endogenic fire	-	Material "sweating", emergence of ethane, slightly tarry odor	Light-grey smoke, noticeable tarry odor
Approximate temperature (°C) in the interior of the heap	-	80–130	300–370
Phase of the development of an endogenic fire	-	Self-propelled isothermal oxidation	Self-heating / self-combustion

The temperature on the substrate is expressed as mean ± standard deviation.

Classification of vegetation

The classification of the vegetation based only on floristic criteria enabled 12 vegetation units to be distinguished. They contained from 3 to 13 relevés and from 28 to 95 vascular species occur in their floristic composition (Tab. 2). The characteristics of plant communities that were distinguished are given below:

- *Medicago lupulina-Festuca pratensis* (Ml-Fp) community: a meadow-like community; average height of the herb layer is 46 cm, the cover of vegetation reaches 54%. The diagnostic species are *Medicago lupulina*, *Festuca pratensis*, *Arrhenatherum elatius*, and *Cirsium oleraceum*. The mean thickness of the layer of dead organic matter is 1.9 cm. Medium-sized patches (60 m^2) of the community were recorded in the nonthermally active zone in sites that are generally open on southern slopes, which are inclined at an angle of 15–30°.
- *Melilotus alba-Achillea millefolium* (Ma-Am) community: a ruderal community, average height of the herb layer is 125 cm and cover was 62%. The diagnostic species is *Achillea millefolium* and *Melilotus alba* is the dominant species. The mean thickness of the layer of dead leaves is 1.0 cm. Large patches (200 m^2) of this phytocoenose occur in a thermally inactive zone in sunny places on the top of the coal mine heap.
- *Tussilago farfara* (Tf) community: the initial community is dominated by the ruderal species *Tussilago farfara*; the average height of the herb layer is 20 cm and cover is 39% and the mean thickness of dead organic matter is 0.9 cm. *Melilotus alba* occurs in a higher abundance in some patches of the community. Small in surface patches (50 m^2) of the community have developed in a thermally inactive zone on sites with strong insolation on the steep southern and southwestern slopes of the dump (35°).
- *Poa annua-Polygonum aviculare* (Pa-Pa) community: a community with diagnostic species such as: *Poa annua*, *Polygonum aviculare*, *Polygonum persicaria*, *Plantago media*, and *Plantago lanceolata*; average height of the herb layer is 20 cm and cover 53%. No dead organic matter was recorded. Medium-sized stands (105 m^2) occur in a thermally inactive zone on sunny, trampled sites on the top of the heap.
- *Phragmites australis* (Phr) community: a medium-sized (110 m^2) reed community with *Phragmites australis* as a dominant. The average height of the herb layer is 154 cm, the percentage of cover is 66% and thickness of the dead organic matter is 6.6 cm. *Solidago gigantea* occurs with a high abundance in some patches. This reed community has developed in shallow depressions on open sites in a thermally inactive zone on the top of the heap.
- *Salix caprea-S. purpurea* (Sc-Sp) community: willow thickets with an average height of 265 cm and a cover of 43% with diagnostic species such as *Salix caprea* and *S. purpurea*. *Calamagrostis epigejos* and *Solidago gigantea* dominate in the herb layer. The mean height of the herb layer is 112 cm and the cover of vegetation 64%. The mean thickness of dead organic matter is 6.1 cm. Large patches of the community (240 m^2) occur in a thermally inactive eastern and southeastern part on the top of the heap.

Tab. 2 A shortened synoptic table of the vegetation on the postmining "Ruda" heap.

	Layer of vegetation	Plant communities											
		Ml-Fp	Ma-Am	Tf	Pa-Pa	Phr	Sc-Sp	Bm-Bp	Ce-Rp	Ta	Cc	Sg	Cv-Ss
Zones of thermal activity		I	I	I	I	I	I	I	I	II	II	II	II
Number of relevés in each vegetation unit		7	10	4	6	4	6	6	13	5	9	10	3
Number of species in each vegetation unit		73	67	37	49	34	52	67	95	28	60	73	36
Cover of trees (%)		2	-	-	-	1	2	64	24	-	-	6	1
Cover of shrubs (%)		5	5	1	-	7	43	17	22	-	-	3	35
Cover of herbs (%)		54	62	39	53	66	64	48	67	53	58	65	40
Height of trees (cm)		597	-	-	-	505	551	1,480	632	-	-	613	570
Height of shrubs (cm)		207	243	-	-	228	265	195	245	-	-	176	116
Height of herbs (cm)		46	125	20	20	154	112	63	125	38	56	109	34
Thickness of dead organic matter (cm)		1.9	1.0	0.9	-	6.6	6.1	6.8	12.8	2.0	2.1	7.0	2.6
Surface of a single relevés (m^2)		25	25	25	25	25	25	100	25	25	25	25	25
Medium surface of the patch (m^2)		60	200	50	105	110	240	260	440	130	380	220	60
Medicago lupulina	c	38.4	-	-	-	-	-	-	-	-	-	-	-
Festuca pratensis	c	30.6	-	-	-	-	-	-	-	-	-	-	-
Arrhenatherum elatius	c	26.5	-	-	-	-	-	-	-	-	-	-	-
Cirsium oleraceum	c	26.1	-	-	-	-	-	-	-	-	-	-	-
Achillea millefolium	c	-	28	-	11.7	-	-	-	-	-	-	-	-
Tussilago farfara	c	-	-	47.4	-	-	11.1	-	-	-	-	-	-
Poa annua	c	9.6	-	-	49.2	-	-	-	-	-	-	-	-
Polygonum aviculare	c	-	-	-	48.1	-	-	-	-	-	-	-	-
Plantago media	c	-	9	-	39.4	-	-	-	-	-	-	-	-
Polygonum persicaria	c	-	-	-	28.3	-	-	-	-	-	-	-	-
Plantago lanceolata	c	-	7.9	-	26	-	-	-	-	-	-	-	-
Phragmites australis	c	-	-	-	-	62.9		-	0.5	-	-	-	-
Salix caprea	b	-	-	-	-	-	33.5	-	13.4	-	-	-	-
Salix purpurea	a	-	-	-	-	-	29.8	-	7.6	-	-	-	-
Salix purpurea	b	-	-	-	-	-	25.2	-	3.6	-	-	-	-
Briza media	c	-	-	-	-	-	-	63.4	-	-	-	-	-
Betula pendula	a	-	-	-	-	-	-	59.4	-	-	-	-	-
Populus tremula	a	-	-	-	-	-	-	58.9	-	-	-	-	-
Poa nemoralis	c	-	-	-	-	-	-	47.2	-	-	-	-	-
Festuca gigantea	c	-	-	-	-	-	-	30.4	-	-	-	-	-
Quercus robur	c	-	-	-	-	-	-	29.4	-	-	-	-	-
Rubus idaeus	c	-	-	-	-	-	-	29.4	-	-	-	-	-
Sambucus nigra	b	-	-	-	-	-	-	27.8	-	-	-	-	-
Quercus robur	a	-	-	-	-	-	-	27.8	-	-	-	-	-
Anthriscus sylvestris	c	-	-	-	-	-	-	25.8	-	-	-	-	-
Calamagrostis epigejos	c	-	-	-	-	-	-	-	39.2	-	-	-	-
Robinia pseudacacia	a	-	-	-	-	-	-	-	37.8	-	-	-	-
Robinia pseudacacia	b	-	-	-	-	-	-	-	35.3	-	-	-	-
Trifolium arvense	c	-	-	-	-	-	-	-	-	47	-	-	-
Conyza canadensis	c	9.4	-	-	-	-	-	-	-	-	48.5	-	-
Calluna vulgaris	c	-	-	-	-	-	-	-	-	-	-	-	58.8
Spiraea salicifolia	b	-	-	-	-	-	-	-	-	-	-	-	33.4
Lamium album	c	-	-	-	-	-	-	-	-	-	-	-	33.4

The explanations of the abbreviations of the names of the plant communities were given in the description of vegetation. The species are arranged according to descending values of fidelity. After the species name, the layer (a – trees; b – shrubs; c – herbs) of vegetation in which a species occurs is given.

- *Briza media-Betula pendula* (Bm-Bp) community: a forest-like community with a distinct three-layered structure. The dead organic matter with an average thickness of 6.8 cm is well developed. The tree layer has an average height of 14.8 m and the cover of 64%. It consists of *Betula pendula*, *Populus tremula*, and *Quercus robur*. The shrub layer has a mean height of 195 cm and its cover is 17%. It is dominated by *Sambucus nigra*. The herb layer, which is rich in species, has a height of 63 cm and a percentage cover of about 48%. It consists of species such as *Briza media*, *Poa nemoralis*, *Festuca gigantea*, and seedlings of *Quercus robur*, *Rubus idaeus*, and *Anthriscus sylvestris*. *Solidago gigantea* has a high degree of cover in some patches. Large (260 m^2) forest-like phytocoenose develop in a zone with no thermal activity in the eastern part of the top of the heap.
- *Calamagrostis epigejos-Robinia pseudacacia* (Ce-Rp) community: a community with high abundance of *Calamagrostis epigejos*. It forms large patches (440 m^2). The average height of the herb layer is 125 cm and the cover 67%. The mean thickness of the dead organic matter is 12.8 cm. This community was recorded in a thermally inactive zone in open places on the top of the heap. In some patches, *Robinia pseudacacia* constitutes the tree and shrub layer with mean heights of 632 cm and 245 cm, respectively. The percentage cover of the tree layer is 24% and the shrub layer 22%.
- *Trifolium arvense* (Ta) community: a grassland community with a high abundance of *Trifolium arvense*. The average height of the herb layer is 38 cm, the percentage cover 53%, the mean thickness of the dead organic matter reaches 2.0 cm. Medium-sized patches (130 m^2) of the community develop in a zone with increased thermal activity on the northwestern slopes of the heap which are inclined at an angle 20–30° in places with high insolation.
- *Conyza canadensis* (Cc) community: large patches (380 m^2) that are dominated by *Conyza canadensis* occur in a zone that has increased thermal activity in sunny places on the steep (15–35°) northwestern slopes of the dump. Mean height of the herb layer is 56 cm and cover was 58%. The average thickness of the layer of dead leaves is 2.1 cm.
- *Solidago gigantea* (Sg) community: an aggregative community with a dominance of *Solidago gigantea*. The average height of the herb layer is 109 cm and its percentage cover 65%. The dead organic matter has a thickness of 7.0 cm. Patches that occupy large areas (220 m^2) develop in a zone with increased thermal activity on the steep northwestern slopes of the heap (20–30°) on highly insolated sites.
- *Calluna vulgaris-Spiraea salicifolia* (Cv-Ss) community: small patches (60 m^2) were created during reclamation works in a zone that have increased thermal activity in slightly shaded places on the northwestern slopes with a slope 5–40°. The shrub layer is 116 cm in height and the cover of 35% mainly consists of *Spiraea salicifolia* and sometimes also *Salix purpurea*. The herb layer reaches an average height of 34 cm and the percentage of cover 40%. It mainly consists of *Calluna vulgaris* and *Lamium album*. The mean thickness of the dead organic matter is 2.6 cm. This community was completely burned out in 2017 due to an intensification of the thermal activity in this part of the heap.

Ordination of plant communities

The DCA analysis shows two long gradients along the first (4.80 *SD* units) and second (3.22 *SD* units) DCA axes. Axis 1 and Axis 2 explain 7.47% and 4.51% of variation, respectively. The eigenvalues of the first and second DCA axes are 0.54 and 0.33, respectively.

The first DCA axis is negatively correlated with light, positively correlated with moisture and weakly correlated with productivity. In contrast, the second DCA axis is negatively correlated with the temperature of the substrate and positively correlated with the soil reaction (Tab. 3).

The herb communities mainly occur on the left side of the diagram: the meadow-like community (*Medicago lupulina-Poa pratensis*), the ruderal community (*Melilotus alba-Achillea millefolium*, *Tussilago farfara*, *Poa annua-Polygonum aviculare*), as well as the reed community (*Phragmites australis*). They are found in open places, drier sites, and sites that are poorer in nutrients. Some of the ruderal phytocoenoses mentioned such

Tab. 3 Kendall's rank correlation coefficients (Tau) between the selected ecological indicator values and the DCA Axes I and II.

Indicators	Axis I	Axis II
Light	**−0.3853**	0.0041
Moisture	**0.2211**	0.0962
Soil reaction	−0.0036	**0.2155**
Nutrient	**0.1599**	−0.1065
Temperature of the substrate	0.0068	**−0.2313**
Thickness of the dead organic matter	**0.4840**	0.0239

Statistically significant ($p \leq 0.05$) correlations are given in bold.

as *Melilotus alba-Achillea millefolium*, *Tussilago farfara*, and *Poa annua-Polygonum aviculare* are also confined to alkaline soil conditions. The forest-like communities (*Briza media-Betula pendula*) is represented on the right side of the DCA dendrogram. The species that occur in their floristic composition are confined to sites that are shaded, wetter and richer in nutrients. A thick layer of dead organic matter was also recorded. The second DCA axis is connected with the gradient of the thermal activity. In the lower part of the DCA diagram plant communities with a floristic composition of species that are confined to open sites and a dry and acid substrate (*Conyza canadensis*, *Calluna vulgaris-Spiraea salicifolia*, *Solidago gigantea*, *Trifolium arvense*). The *Calamagrostis epigejos-Robinia pseudacacia* community and willow thickets (*Salix caprea-S. purpurea*), which occur on shaded sites on wet and alkaline soils are concentrated in the middle and top of the DCA ordination diagram. They also have a thick layer of dead organic matter (Fig. 2).

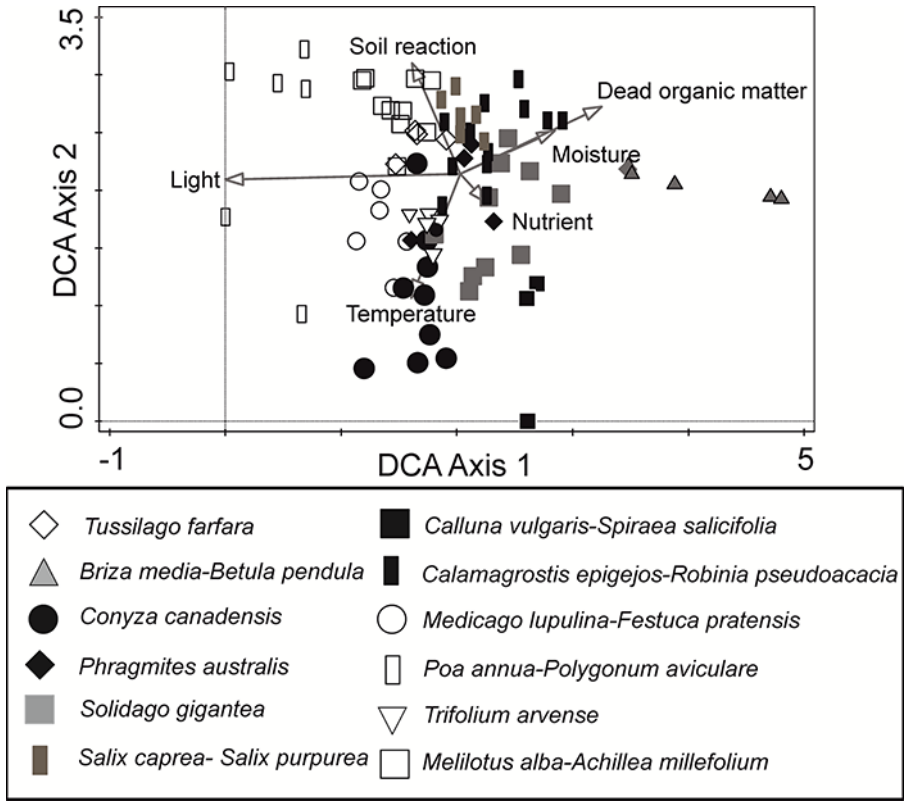

Fig. 2 Ordination diagram of the DCA analysis for the vegetation on the postmining "Ruda" heap.

Effect of thermal activity on the species richness and species diversity of plant communities

A statistically significant effect of the thermal activity on species richness ($Z = 2.13$, $p = 0.03$) and species diversity ($Z = 2.29$, $p = 0.02$) of the plant communities of the dumping ground was found (Fig. 3).

The plant communities that were recorded in the thermally inactive zone are generally richer in species (No. = 22.03) and are more diverse ($H' = 2.19$) than those that are located in places with higher temperature (No. = 15.24, $H' = 1.81$). Some exceptions

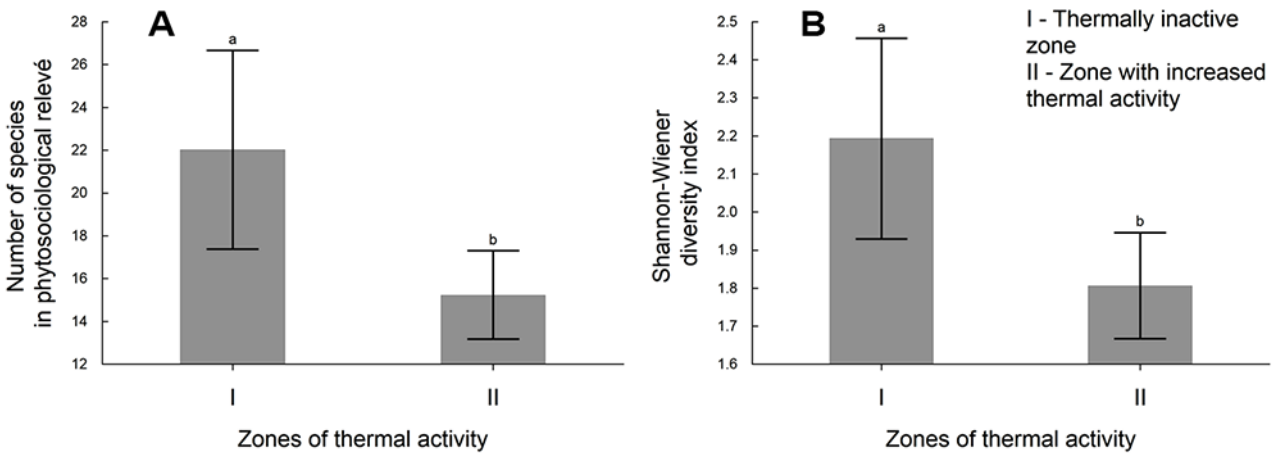

Fig. 3 Comparison of the zones with different levels of thermal activity on the postmining "Ruda" heap in relation to species richness (**A**) and species diversity (**B**). The zones examined are significantly different in terms of species richness ($Z = 2.13$, $p = 0.03$) and species diversity ($Z = 2.29$, $p = 0.02$) according to the Mann–Whitney nonparametric U test. The values represent means ± standard deviation.

Tab. 4 Comparison of the zones that had different levels of thermal activity on the postmining "Ruda" heap in relation to species richness and species diversity.

Zones of thermal activity	Plant communities	No.	H'
Thermally inactive	Ml-Fp	26.43	2.69
	Ma-Am	25.30	2.23
	Tf	17.25	1.92
	Pa-Pa	18.17	1.95
	Phr	15.00	1.92
	Sc-Sp	22.33	2.25
	Bm-Bp	24.50	2.34
	Ce-Rp	27.23	2.24
	Mean	22.03	2.19
	Standard error	1.64	0.09
	Standard deviation	4.64	0.26
With increased thermal activity	Ta	13.40	1.62
	Cc	14.67	1.82
	Sg	18.20	1.84
	Cv-Ss	14.67	1.95
	Mean	15.24	1.81
	Standard error	1.03	0.07
	Standard deviation	2.07	0.14

No. – the number of species that were recorded in the relevé; H' – the Shannon–Wiener diversity index. See the description of vegetation for explanations of the abbreviations of the names of the plant communities.

are the reed community, which is dominated by *Phragmites australis* (No. = 15.00, $H' = 1.92$), the initial phytocoenoses with *Tussilago farfara* (No. = 17.25, $H' = 1.92$) and *Poa annua-Polygonum aviculare* community on trampled sites (No. = 18.17, $H' = 1.95$) (Tab. 4).

The highest species richness and species diversity were recorded for the meadow-like (*Medicago lupulina-Festuca pratensis*: No. = 26.43, $H' = 2.69$) and forest-like (*Briza media-Betula pendula*: No. = 24.50, $H' = 2.34$) phytocoenoses, willow thickets with *Salix caprea* and *S. purpurea* (No. = 22.33, $H' = 2.25$), patches of *Calamagrostis epigejos* and *Robinia pseudacacia* (No. = 27.23, $H' = 2.24$), and the ruderal communities with *Melilotus alba* and *Achillea millefolium* (No. = 25.30, $H' = 2.23$), which develop on sites with a lower temperature on the southern slopes and on the top of the dumping ground (Tab. 4).

The poorest and the least diverse are the grasslands with *Trifolium arvense* (No. = 13.40, $H' = 1.62$), large surface aggregations of *Conyza canadensis* (No. = 14.67, $H' = 1.82$) and *Solidago gigantea* (No. = 18.20, $H' = 1.84$), and the community that was created by *Calluna vulgaris* and *Spiraea salicifolia* (No. = 14.67, $H' = 1.95$), which occurs on warm substrates on the steep northwestern slopes of the heap (Tab. 4).

Discussion

An unprecedented occurrence of a mosaic of sometimes extreme habitats can be observed on postmining heaps [2,20]. Many abiotic and biotic factors are responsible for development, as well as further differentiation of vegetation. One of them is thermal activity that has influence on both physical and chemical properties of the substrate [1,2,21].

Endogenous thermal activity was observed on the steep (15–40°) northwestern slopes of the spoil heap. The average temperature of the substrate was 60.2°C and the

temperature inside it reached 300–370°C [7,8]. The thermally active zone is devoid of any permanent plant cover. Moreover, the *Calluna vulgaris-Spiraea salicifolia* community which was created during reclamation work has disappeared completely due to the increase of the area that was impacted by fire. Extremely high temperatures can cause a significant acidification and increased salinity of the substrate, as well as the burning of plant roots and the disappearance of any seed banks in the soil [22,23]. The gases emanating from a fire also contain a number of substances that can be toxic to plants (including CO_2, CO, CH_4, NO_2, SO_2, H_2S, HF, NH_3, HCl, aromatic hydrocarbons, Hg, As, Pb, Se) [21].

The vegetation of the study area is formed along the gradient of the thermal activity of the substrate. At distances further away from the sites with increased thermal activity from the northwestern slopes of the heap towards the east, an increase in the development of spontaneous vegetation succession was observed. The number of plant communities (from four to eight), as well as species richness (number of species from 15 to 22) and species diversity (H' from 1.81 to 2.19) both increase. Native, perennial species begin to dominate in the species composition of the vegetation. The soil reaction and moisture as well as the amount of dead organic matter also increase. The structure of plant communities becomes more complex moving from one–two layered to three layered. Increases in the shading of the substrate enable the development of shade-loving forest species [1,2,22,24].

The zone that has an increased thermal activity is in the immediate vicinity of the thermally active parts of the coal mine heap. The vegetation that occurs here is characterized by both a low species richness (No. = 15.24) and a low species diversity (H' = 1.81). Large (380 m^2) and medium-sized (130 m^2) pioneer communities of therophytes (*Conyza canadensis*, *Trifolium arvense*), which produce a large number of seeds and begin to flower relatively early during the vegetative season have developed in sunny places on the dry and acidic substrate. Aggregations of *Solidago gigantea*, which produce strong underground stolons and are characterized by a wide range of ecological tolerance, are also found here occupying a large area (220 m^2) [6,23]. Rostański [1], Woźniak [2], and Banaszek et al. [20] also found such aggregations of *S. gigantea* on other coal mine heaps in the Upper Silesia Industrial Region (southwestern Poland). The dominance of invasive kenophytes (*C. canadensis*, *S. gigantea*) is typical of initial habitats that have an unstable plant cover [22,24]. An increased temperature >30°C causes disturbances in the functioning of the root systems of plants and changes in the height of plants (38–109 cm) as well as necrosis and drying of leaves [21,22].

A thermally inactive zone with an average ground temperature of 25.4°C covers the top, the southern, and southwestern slopes of the spoil heap. The vegetation developing here is characterized by a dominance of native species, a higher species richness (No. = 22.03) and species diversity (H' = 2.19) [1,2,22]. In open and highly sunny places on drier and alkaline substrates, the initial stage of the development of the spontaneous plant cover is represented by *Tussilago farfara* patches and communities of *Poa annua* and *Polygonum aviculare* on trampled sites. Communities of the intermediate stage of succession, such as meadow-like stands with *Medicago lupulina* and *Festuca pratensis*, ruderal communities with *M. alba* and *Achillea millefolium*, and reeds with *Phragmites australis* that tolerate drought, were also recorded on these sites [1,2,22,25,26]. In the intermediate stage of plant succession, the plant-forming activities of the expansive, clonal and tall grass (125 cm) *Calamagrostis epigejos* is important. This species forms compact and large area patches (440 m^2) in open and slightly shaded places on wet and alkaline substrates on the top of the heap. The decomposition of the thick layer of its fallen leaves (12.8 cm) improves the edaphic properties of the soil substrate, which enables the further development of the plant cover and the encroachment of more specialized species, such as *Salix caprea* and *S. purpurea* [1,20,25–28]. On wet and alkaline substrates in the eastern part of the top of dumping grounds, a forest-like community with a distinct three-layer structure has developed. A compact (64%) stand has been built by *Betula pendula*, *Populus tremula*, and *Quercus robur*. The increase in the shading, moisture, and fertility of the substrate allows the development of the vegetation of the undergrowth, which is mainly built by forest species, such as *Poa nemoralis* or *Festuca gigantea* [1,2,20,24,26].

Our study showed a statistically significant effect of thermal activity on species richness ($Z = 2.13$, $p = 0.03$) and species diversity ($Z = 2.29$, $p = 0.02$), as well as on the

differentiation of the vegetation of the postmining heap "Ruda" in Zabrze. Similar results were obtained by Rostański [1], Woźniak [2], Banaszek et al. [20], and Ciesielczuk et al. [22] during studies on flora and vegetation of other coal mine spoil heap of Upper Silesia (southwestern Poland).

Acknowledgments

We would like to thank dr hab. Wojciech Bąba for fruitful discussion on the manuscript, as well as the anonymous reviewers for valuable suggestions which have enabled us to significantly improve the scientific value of the work.

References

1. Rostański A. Spontaniczne kształtowanie się pokrywy roślinnej na zwałowiskach po górnictwie węgla kamiennego na Górnym Śląsku. Katowice: Wydawnictwo Uniwersytetu Śląskiego; 2006.
2. Woźniak G. Zróżnicowanie roślinności na zwałach pogórniczych Górnego Śląska. Kraków: Instytut Botaniki im. W. Szafera, Polska Akademia Nauk; 2010.
3. Dulewski J, Madej B, Uzarowicz R. Zagrożenie procesami termicznymi obiektów zagospodarowania odpadów z górnictwa węgla kamiennego. Gospodarka Surowcami Mineralnymi. 2010;26(3):125–142.
4. Drenda J, Różański Z, Słota K, Wrona P. Zagrożenie pożarowe na zwałowiskach odpadów powęglowych. Górnictwo i Geoinżynieria. 2007;31(3):149–157.
5. Solon J, Borzyszkowski J, Bidłasik M, Richling A, Badora K, Balon J, et al. Physico-geographical mesoregions of Poland: verification and adjustment of boundaries on the basis of contemporary spatial data. Geogr Pol. 2018;91(2):143–170. https://doi.org/10.7163/GPol.0115
6. Hanczaruk R. Spektrum ekologiczno-siedliskowe flory naczyniowej zwałowiska odpadów pogórniczych "Ruda" w Zabrzu-Biskupiach. Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu. 2017;494:50–63. https://doi.org/10.15611/pn.2017.494.05
7. Korski J. Ocena skuteczności technologii gaszenia składowiska odpadów powęglowych "Ruda" w świetle badań terenowych. Górnictwo i Geologia. 2009;4(2b):87–98.
8. Wasilewski S, Korski J. Wczesne wykrywanie pożarów jako element monitoringu składowisk odpadów powęglowych. Mechanizacja i Automatyzacja Górnictwa. 2010;48(8):3–17.
9. Braun-Blanquet J. Pflanzensoziologe. Grundzuge der Vegetationskunde. 3rd ed. Wien: Springer Verlag; 1964.
10. Dzwonko Z. Przewodnik do badań fitosocjologicznych. Poznań: Sorus; 2007.
11. Perzanowska J, editor. Monitoring gatunków roślin. Przewodnik metodyczny. Część I. Warszawa: Główny Inspektorat Ochrony Środowiska; 2010.
12. Mirek Z, Piękoś-Mirkowa H, Zając A, Zając M, editors. Flowering plants and pteridophytes of Poland – a checklist. Kraków: W. Szafer Institute of Botany, Polish Academy of Sciences; 2002. (Biodiversity of Poland; vol 1).
13. Tichý L, Holt J. JUICE: program for management, analysis and classification of ecological data. Brno: Vegetation Science Group, Masaryk University; 2006.
14. Tichý L. JUICE, software for vegetation classification. J Veg Sci. 2002;13(3):451–453. https://doi.org/10.1111/j.1654-1103.2002.tb02069.x
15. Tichý L, Holt J, Nejezchlebová M. JUICE program for management, analysis and classification of ecological data. 2nd edition of the program manual. 2nd part. Brno: Vegetation Science Group, Masaryk University; 2010.
16. Ellenberg H, Weber HE, Düll R, Wirth V, Werner W, Paulissen D. Zeigerwerte von Pflanzen in Mitteleuropa. 2nd ed. Göttingen: Goltze; 1992. (Scripta Geobotanica; vol 18).
17. Ter Braak CJF, Šmilauer P. CANOCO reference manual and user's guide: software for ordination, version 5.0. Ithaca, NY: Microcomputer Power; 2012.
18. Šmilauer P, Lepš J. Multivariate analysis of ecological data using CANOCO 5. 2nd ed. Cambridge: Cambridge University Press; 2014.

https://doi.org/10.1017/CBO9781139627061

19. Dell Inc. STATISTICA (data analysis software system). Version 13 [Software]. 2016 [cited 2019 Feb 22]. Available from: http://software.dell.com/
20. Banaszek J, Leksy M, Rahmonov O. The role of spontaneous succession in reclamation of mining waste tip in area of Ruda Śląska City. Environmental Engineering: Proceedings of the International Conference on Environmental Engineering; 2017;2017:enviro.2017.098. https://doi.org/10.3846/enviro.2017.098
21. Zając E, Zarzycki J. Wpływ aktywności termicznej zwałowiska odpadów węgla kamiennego na rozwój roślinności. Rocznik Ochrona Środowiska. 2013;15:1862–1880.
22. Ciesielczuk J, Czylok A, Fabiańska MJ, Misz-Kennan M. Plant occurrence on burning coal waste – a case study from the Katowice-Wełnowiec dump, Poland. Environmental and Socio-economic Studies. 2015;3(2):1–10. https://doi.org/10.1515/environ-2015-0057
23. Hanczaruk R, Gołąb N. Wybrane problemy rekultywacji zwałowiska odpadów pogórniczych na przykładzie zwałowiska "Ruda" w Zabrzu-Biskupiach. Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu. 2016;461:65–75. https://doi.org/10.15611/pn.2016.461.06
24. Woch MW, Radwańska M, Stefanowicz AM. Flora of spoil heaps after hard coal mining in Trzebinia (southern Poland): effect of substratum properties. Acta Bot Croat. 2013;72(2):237–256. https://doi.org/10.2478/v10184-012-0020-x
25. Rostański A, Woźniak G. Trawy (Poaceae) występujące spontanicznie na terenie nieużytków poprzemysłowych. In: Frey L, editor. Biologia traw. Kraków: Instytut Botaniki im. W. Szafera, Polska Akademia Nauk; 2007. p. 31–42. (Fragmenta Floristica et Geobotanica Polonica, Supplementum; vol 9).
26. Woźniak G, Markowicz A, Borymski S, Piotrowska-Seget Z, Chmura D, Besenyei L. The relationship between successional vascular plant assemblages and associated microbial communities on coal mine spoil heaps. Community Ecol. 2015;16(1):23–32. https://doi.org/10.1556/168.2015.16.1.3
27. Sheoran V, Sheoran AS, Poonia P. Soil reclamation of abandoned mine land by revegetation: a review. Int J Soil Sediment Water. 2010;3(2):1–20.
28. Rahmonov O, Parusel T. Vegetation succession and soil development in an area transformed by human impact – reclaimed ash landfills. In: Proceedings of the 8th International Conference on Environmental Engineering; 2011 May 19–20; Vilnius, Lithuania. Vilnius: Gediminas Technical University; 2011. p. 323–330.

Wpływ aktywności termicznej na zróżnicowanie roślinności zwałowiska odpadów pogórniczych „Ruda" w Zabrzu (Polska)

Streszczenie

W artykule przedstawiono wyniki badań nad roślinnością aktywnego termicznie zwałowiska odpadów pogórniczych "Ruda" w Zabrzu. Celem badań było: (***i***) przedstawienie zróżnicowania roślinności, która rozwinęła się w wyniku aktywności termicznej oraz (***ii***) określenie wpływu aktywności termicznej zwałowiska na bogactwo gatunkowe i różnorodność gatunkową roślinności. Na hałdzie odnotowano 12 zbiorowisk roślinnych. Wykazano istotny statystycznie wpływ aktywności termicznej na bogactwo gatunkowe ($Z = 2{,}13$; $p = 0{,}03$) i różnorodność gatunkową ($Z = 2{,}29$; $p = 0{,}02$) roślinności zwałowiska. Skład gatunkowy zbiorowisk roślinnych odzwierciedla warunki siedliskowe panujące na hałdzie, które uwarunkowane są przez aktywność termiczną. Wraz ze wzrostem odległości od strefy o podwyższonej aktywności termicznej wzrasta stopień zaawansowania spontanicznej sukcesji roślinności. Zmniejsza się udział obcych i jednorocznych gatunków na rzecz wieloletnich, rodzimych roślin. Wzrasta liczba zbiorowisk roślinnych (od czterech do ośmiu) oraz ich bogactwo gatunkowe (liczba gatunków – od 15 do 22) i różnorodność gatunkowa (wskaźnik różnorodności Shannona–Wienera – od 1,81 do 2,19). Nietendencyjna analiza zgodności (DCA) wykazała wzrost zacienienia, wilgotności i odczynu podłoża oraz grubości warstwy martwej materii organicznej w gradiencie aktywności termicznej.