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Original Research

Vegetation of Reclaimed and Spontaneously Vegetated Zn-Pb Mine Wastes in Southern Poland

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Abstract

In 2004, soil properties and the species composition of vascular plants and lichens were studied at five sites in a former zinc and lead mining region (Olkusz region, southern Poland). The sampled sites, four reclaimed by planting trees differed in age (5, 15, 30, 35 years old), and one spontaneously vegetated (100 years old). The sites were similar in soil structure and chemical composition. These were skeletal soils poor in N and P, and rich in Ca, Mg, Zn, Pb and Cd. The 100-year vegetation which has developed there spontaneously is represented by grasslands formed mostly by species of open, dry, warm, calcareous and metalliferous habitats, with a numerous group of lichens. On sites with planted trees, the herb layer plants appeared as the result of spontaneous colonization. In the herb layer of younger sites there were species typical of spontaneously developed grassland. Older sites harbored fewer grassland species but also included shade-tolerant meadow species. Expansion of trees caused the disappearance of species characteristic of metalliferous waste habitats. Though tree planting accelerates the formation of plant cover in post-mining areas, it is not conducive to the maintenance of the specific composition of local plant species. Spontaneous development of local vegetation seems an appropriate way to rehabilitate at least part of post-mining areas with regard to the maintenance of the vegetation typical for the metalliferous soils. Islands of such vegetation increase the biodiversity of degraded areas.

Keywords: post-mining area, metalliferous soils, reclamation, afforestation, grasslands

Introduction

Extraction of minerals by means of opencast mining destroys the land surface. Mining work creates huge opencasts and a large amount of waste, mainly rock waste, and leaves a bare surface. The development of vegetation is as a rule difficult and protracted in these areas, due to the unfavorable physical and chemical properties of the waste, as well as the limited pool of appropriate species which could colonize them [1]. Nevertheless, vegetation colonizes these areas and often forms distinctive and valuable communities [2]. Natural development of vegetation is unfortunately a rare phenomenon in post-mining areas in Poland because the enterprise that caused the degradation of the land is obliged by law to reclaim it. As a rule, the aim of reclamation work is to introduce any plant cover that can protect the waste against surface erosion and can accelerate the development of soil. The oldest traditional way of reclaiming areas degraded by human activity is to plant trees and shrubs. Species adapted to the habitat conditions of a given area are used only rarely. The planted species are usually birch, larch and pine, which are relatively resistant to drought and to nutrient scarcity. This mode of reclamation produces large areas of single species woodlands with low biological diversity.

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In the Wyżyna Śląsko-Krakowska upland of southern Poland there are rich deposits of zinc and lead ores. Extraction of these deposits, carried out for at least 800 years, destroyed large expanses of land. Mining waste, rich in heavy metals, and extensive opencasts now cover hundreds of hectares. These areas were and are still being afforested by planting of trees and shrubs. After planting, vegetation develops without human intervention. Forests and woodlots of different ages and states of health, formed of one or several species, are characteristic features of the present landscape of this post-mining area. One can also find scarce patches of spontaneously developing vegetation on metalliferous mine waste. Studies of several plant species (e.g. *Biscutella laevigata, Armeria maritima, Dianthus carthusianorum*) originating from these places have shown that they differ morphologically, anatomically, physiologically and genetically from plants growing outside the metalliferous areas [3]. Apart from these investigations, no comprehensive studies of the vegetation have been carried out in this area, which is characteristic of industrialized southern Poland. The aims of the present study on the mine waste area were:

1. to determine soil conditions and vegetation composition,
2. to find the factor influencing vegetation diversity,
3. to determine what is the impact of land reclamation (due to tree planting) on vegetation development,
4. to specify the natural value of the vegetation.

Study Area

The study was carried out in an area between Bukowno (50º15'46" N, 19º26'29" E) and Bolesław (50º17'50' N, 19º28'50" E), where zinc and lead ores were once mined. It lies within the Olkusz region, which has the richest Zn-Pb deposits in southern Poland.

The Zn-Pb ores of the Olkusz region occur in Triassic sediments, mainly ore-bearing dolomite and, rarely, limestone. They contain more than a dozen minerals. The basic ones are zinc sulphides (ZnS), lead sulphides (PbS) and iron sulphides (FeS). They are accompanied by secondary minerals originating from oxidation and carbonization processes and minerals containing other elements such as Cd, Ag and Tl [4].

Zn-Pb ore was extracted in the Olkusz region from the 12th century to the late 1990s. Opencast mining left an area devoid of vegetation, with deep pits and huge amounts of different kinds of waste. The largest area is covered by mining rock waste, rock overlaying the deposit, and rock from the deposit. The waste was usually deposited around opencasts in heaps of different sizes. In the environs of Bukowno and Bolesław, mine waste was accumulated during several periods. The oldest waste dates back to the 19th century, and more recent waste to the latter part of the 20th century. It comes from the exploitation of two large deposits of Zn-Pb ores, called the Bolesław and Krążek deposits [4].

Environmental degradation in the Olkusz region is also related to atmospheric pollution. Up to the end of the 1980s, the area had the highest atmospheric deposition of sulphur and dust with heavy metals in Poland. Dust emissions from ore processing alone were then about 500 $t \cdot yr^{-1}$, and SO_2 over 5,000 $t \cdot yr^{-1}$. Currently that industry annually emits only about 1.5 t of dust and about 400 t SO_2 (unpublished data of the Bolesław Mining and Smelting Works).

Degraded post-mining areas should be reclaimed. In the post-mining area between Bukowno and Bolesław, reclamation work started in the 1970s. It was carried out by the Bolesław Mining and Smelting Works (ZGH "Bolesław"), which was responsible for degradation of the area. Reclamation consisted in leveling the ground and planting trees and shrubs. As a result, these areas are now covered mostly by woodlands of different ages, with artificially introduced birch (*Betula pendula*), larch (*Larix decidua*), pine (*Pinus sylvestris*) and black locust (*Robinia pseudoacacia*).

Material and Methods

In the Bolesław-Bukowno mining region, five 0.5 ha study sites were selected. Four sites (R5, R15, R30, R35) were reclaimed by planting trees and shrubs. Study site R5 was afforested in 1998, R15 at the end of the 1980s, and R30 and R35 in 1970-78. The exact date of planting was documented only for R5. Earlier planting work carried out in community campaigns was not registered. Judging from the present age of trees and from inquiries at ZGH "Bolesław" responsible for reclamation work, it is likely that planting at R15 was done about 15 years before the study was started, and 30-40 years at R30 and R35. The fifth study site (NR100) has never been reclaimed; mine waste accumulated there at the end of the 19th century was spontaneously colonized by vegetation.

Ten permanent circular plots (each 100 m^2 in area) were established at each of the study sites. At each site they were selected randomly. Places with untypical surface features (ditches, paths) were excluded. The study was carried out in summer 2004.

Around each plot, 5 samples of the surface soil (to 10 cm depth) were taken with a soil auger (diameter 10 cm). These samples were bulked into one sample per plot. In addition, one soil profile was dug at each site, and the depth of the distinguished horizons and their granulometric composition were determined by Prószyński's method.

In the mixed samples (n=50) from the upper soil layer, pH, effective cation exchange capacity (CEC), and concentrations of elements (C, N, P, K, S, Ca, Mg, Zn, Pb, Cd) were measured. Acidity (pH) was determined potentiometrically, C organic content by Turin's method, S concentration by the coulometric method with a CS 30 Behr Analyzer, N by Kjeldahl's method with a Kjeltec 2003 apparatus, and P colorimetrically by the vanadium-molybdenum method [5]. Total concentrations of Ca, Mg, Zn, Pb and Cd were determined in samples (1 g of soil) mineralized in hot concentrated perchloric acid (10 ml of $HClO_4$).

Table 1. Proportion of granulometric fractions in soil profile horizons on reclaimed (R5, R15, R30, R35) and spontaneously vegetated (NR100) mine waste.

Site	Layer	Depth	Proportion of granulometric fractions		
			1-0.05	0.05-0.002	<0.002
		cm	%		
R5	Ao	2-1	69	26	5
	A1	2-5	49	46	5
	C	5-25	52	43	5
R15	Ao	0-5	73	24	3
	A1	5-9	62	36	2
	A1/A2	9-20	60	37	3
	A2	20-50	54	41	5
	C	>50	56	39	5
R30	Ao	0-6	73	23	4
	A1	7-40	68	29	3
	A2	40-65	85	11	4
	C	>65	57	19	24
R35	Ao	0-7	61	37	2
	A1	7-22	35	63	2
	A2	22-50	45	50	5
	C	>50	50	45	5
NR100	Ao	0-5	65	31	4
	A1	5-40	53	42	5
	C	>40	51	41	8

The cation exchange capacity (CEC) measurements were based on ion exchange reactions using barium chloride ($BaCl_2$). 3 g soil samples were mixed with 30 ml 0.1M aqueous $BaCl_2$ solutions (pH=7) [5]. The suspensions were shaken (2 h at slow speed) and filtered. In extracts the CEC and exchangeable Zn, Cd, Pb were measured. Atomic absorption spectrometry (AAS; Varian 220 FS) was used to determine concentrations of the exchangeable cations and total elements in soil samples. In all soil samples the amount of exchangeable Pb was below the detection limits of the method used (<0.5 mg/l). For all chemical analyses the <2 mm soil fraction was used.

In each plot (n=50), vascular plants and lichens were identified. The cover of particular species was determined according to Braun-Blanquet's six-grade scale (+ to 5). The nomenclature for vascular plant species follows Mirek et al. [6], and for lichens follows Bielczyk [7]. An ecological indicator value (based on habitat requirements) was ascribed to each species on the basis of the guidelines given by Zarzycki et al. [8].

Differences in basic soil characteristics between sites were checked for significance with the Kruskall-Wallis non-parametric test and multi-comparison test (LSD). Principal component analysis (PCA) with varimax rotation was applied to separate non-correlated factors describing soil chemistry.

Plant species diversity was described by the number of species and Shannon-Wiener's index of diversity (calculated with the PAST program). The variability of the species number and diversity coefficient between the study sites was estimated by the t test using the JUICE program.

Variability of vegetation at the study sites was analyzed by the Wildi method using the MULVA-5 package [9]. Indirect and direct gradient analyses were used to estimate the relationship between vegetation composition and the environmental variable [10]. The community composition gradient was not long (<2), so the linear ordination method (redundancy analysis, RDA) was used. Statistical analysis were performed using the STATISTICA package and CANOCO 4.5.

Results

Soil Properties

The soils of the investigated sites were shallow, mostly skeletal soils. In the poorly developed profiles only horizons A and C were distinguishable (Table 1). Depending on the horizon and site, the share of sand and silt fraction (particles >0.002 mm) was different, ranged from 35 to 85% and from 11 to 63%, respectively. The clayey fraction (particles <0.002 mm) were rather stable and low (2-8%), except for horizon C of study site R30 (about 24%).

At all sites the upper soil horizons (to 10 cm depth) were alkaline (pH 7.21-7.80) (Table 2). The average content of organic carbon ranged from 9.91% (R5) to 15.5% (R15); for macroelements the concentrations ranged from 0.05% (R5) to 0.46% (R15) for N, from 0.04% (R5) to 0.08% (R15) for P, and from 0.19% (R5) to 0.33% (NR100) for K. The study sites were characterized by high concentrations of other nutrients originating from rock mine waste (Ca 6.43–13.56%, Mg 3.73-7.85%, Zn 3.46-7.57%) and nonessential heavy metals (Pb 0.30-0.46%, Cd 0.010-0.022%) (Table 2). Within all study areas the soils showed high variability in the concentration of the majority of elements (Table 2).

The soil of the youngest reclaimed site (R5) differed significantly from the soil of older sites in most of its chemical properties (Table 2). It had higher pH, lower cation exchangeable capacity (CEC) and lower concentrations of total N, P and exchangeable forms of metals (Zn, Cd) than the soils of other sites. The organic carbon content of R5 did not differ much from the other sites, but the C/N ratio (289) was many times higher than at the other sites (26-87). The concentration of total potassium for the youngest site (R5) differed only from the spontaneously vegetated site (NR100), while its concentrations of total Ca, Mg, Zn, Pb and Cd differed from two older reclaimed sites (R30, R35).

Table 2. Chemical properties of soils from reclaimed (R5, R15, R30, R35) and spontaneously vegetated mine waste (NR100).

Site		R5			R15			R30			R35			NR100		
Parameter		Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
pH		7.8	0.09^{a}	1	7.28	0.12^{b}	2	7.34	0.19^{b}	3	7.21	0.22^{b}	3	7.3	0.26^{b}	4
CEC	molc(+)/kg	8.6	1.9^{a}	22	26.6	8.7^{b}	33	27.7	10.8^{b}	39	27.7	8.2^{b}	30	17.4	6.8^{a}	40
C	%	9.91	0.23^{a}	2	15.5	2.9^{c}	19	10.84	1.62^{ab}	15	10.81	1.68^{ab}	15	12.11	2.68^{bc}	22
N	%	0.05	0.03^{a}	58	0.46	0.17^{b}	37	0.35	0.16^{b}	44	0.43	0.1^{b}	24	0.31	0.13^{b}	43
C/N		289	216^{a}	75	46	20^{b}	44	36	13^{b}	36	26	6^{b}	23	87	49^{a}	56
P	%	0.04	0.01^{a}	8	0.08	0.02^{b}	21	0.06	0.01^{b}	10	0.05	0.01^{b}	17	0.05	0.01^{b}	20
K	%	0.26	0.09^{a}	34	0.19	0.07^{a}	35	0.22	0.09^{a}	40	0.19	0.04^{a}	22	0.33	0.12^{b}	37
Ca	%	13.56	5.57^{b}	41	9.29	1.53^{b}	16	6.7	2.72^{ab}	41	5.78	1.4^{a}	24	6.43	2.15^{ab}	33
Mg	%	7.85	1.8^{a}	23	5.26	0.81^{a}	15	3.93	1.27^{b}	32	3.73	1.08^{b}	23	4.25	1.23^{a}	29
Zn	%	7.57	3.63^{a}	48	5.47	1.93^{a}	35	4.38	3.13^{ab}	72	3.46	1.72^{b}	50	5.15	1.61^{a}	31
Pb	%	0.46	0.15^{a}	33	0.44	0.07^{a}	17	0.43	0.14^{ab}	32	0.3	0.06^{b}	19	0.43	0.17^{a}	41
Cd	%	0.022	0.005^{a}	21	0.019	0.003^{ab}	18	0.019	0.008^{ab}	43	0.01	0.003^{b}	28	0.022	0.007^{a}	30
Zn_{ex}	mg/kg	77	21^{a}	26	320	73^{b}	23	295	144^{b}	49	344	96^{b}	28	227	104^{b}	46
Cd_{ex}	mg/kg	9.3	2.6^{a}	28	22.1	4^{b}	18	28.2	12.2^{b}	43	20.2	3.4^{b}	17	20.5	8.1^{b}	40

Significant differences between sites ($p<0.05$) are indicated by different letters; ex – exchangeable form of element.

Of all the study sites, the soils of R30 and R35 generally contained the lowest amounts of elements originating from rock waste minerals. The older reclaimed sites (R15, R30, R35) and the non-reclaimed site (NR100) did not differ significantly in pH, nor in total content of N, P, K and C.

Table 3 shows the results of factor analysis for the chemical properties of the examined soils. Three factors (F1-F3) explained 76% of the total variability of the chemistry of soils developed on mine waste. In factor 1 (F1) the most important were N, P, C, CEC and exchangeable forms of Cd and Zn. They comprised a positively correlated group. Soil pH was negatively correlated with this group. This factor may thus represent soil organic matter. Factor 2 (F2) comprised the main elements contained in rock mine waste, originating mostly from dolomite together with the remnants of Zn-Pb ores (Ca, Mg, Zn, Pb, Cd). Factor 3 (F3) consists only of K, connected with the mineral soil material.

Vegetation Characteristics

The age and type of site determined the composition of vegetation layers and the degree of plant colonization. The youngest reclaimed site (R5) was characterized by herb layer (C) with average cover of about 50%, and a layer of planted trees forming layer B with average cover of about 40%. At the 15-year-old site (R15), plantations formed both the shrub layer (B, about 30% cover) and lower tree layer (A1, about 40% cover). Its herb layer was abundant (90% cover). At older study sites (R30, R35) the tree layer was fully developed (A1, about 50% cover; A2, about 80% cover). The shrub layer was less abundant (cover to about 20%) and the herb layer abundant (100% and 80% cover). At the oldest study site, representing vegetation spontaneously developing for over 100 years (NR100), there were large patches of grassland vegetation (cover to about 100%) and patches with expanding trees (about 40% cover).

For all study sites there were 116 vascular plant species, and 27 lichen species (Tables 5 and 6). Of the vascular plants, 95 species were herbaceous plants and 21 species were shrubs and trees. Four tree species were planted (*Pinus sylvestris, Larix decidua, Betula pendula, Robinia pseudoacacia*). The remaining woody plants were species that colonized the area spontaneously. Among the herbaceous plants, 8 species were biennials or annuals, and the others perennials. On the basis of the ecological indicator values, most species occurring in the examined sites were determined to be light-demanding (80-90% of the species), preferring dry to fresh soils (about 60% of the species) and moderately acid to alkaline soil (70-80% of the species) (Table 5).

Table 4 shows the species richness (S) and species diversity (H') of the study sites. Only the field layer vegetation was used for comparison because at all sites it had developed spontaneously, unlike the shrub and tree layers, which were mostly introduced by planting. The fewest vascular plant species were noted at the oldest site (NR100) and the youngest reclaimed site (R5), and the most vascular plant species at the 35-year-old site (R35). Species diversity as expressed by coefficient H' ranked the sites from lowest to highest as follows: R30, NR100, R15, R5, R35. For lichens, spontaneously vegetated site (NR100) was richest and most diverse in terms of species number, while reclaimed site R35 was poorest and least diverse.

About 25% of the vascular plant species formed one distinct group common to all study sites (Table 5). It was represented by perennials, usually connected with shallow soils and dry and warm habitats, mostly grassland. The most frequent and abundant species were *Thymus pulegioides, Scabiosa ochroleuca, Pimpinella saxifraga, Galium album*, and also *Silene vulgaris, Dianthus carthusianorum, Cardaminopsis arenosa, Festuca ovina* and *Biscutella laevigata*. They were accompanied by species of slightly more fertile and wetter habitats, such as *Leontodon hispidus, Ranunculus acris* and *Agrostis gigantea*. Among trees, seedlings of oak (*Quercus robur*) and seedlings and undergrowth of pine (*Pinus sylvestris*) commonly occurred. The second group was formed of species occurring frequently and numerously at older reclaimed sites (R15, R30, R35) and rarely at the spontaneously vegetated site (NR100) and the youngest reclaimed one (R5). These species represented a wide spectrum of habitat requirements. Meadow species (*Rumex thyrsiflorus, Carex hirta, Veronica chamaedrys, Trifolium repens*) were accompanied by grassland species (*Helianthemum nummularium, Armeria maritima*) and forest species (*Pinus sylvestris, Malaxis monophyllos*). The third group, occurring almost exclusively at the oldest reclaimed sites (R30, R35), consisted mostly of planted trees (*Larix decidua, Betula pendula*), which were accompanied by grassland and meadow species typical of alkaline soils (*Coronilla varia, Brachypodium pinnatum, Euphorbia cyparissias*) and a few forest species of slightly acid soils (*Pyrola minor, Orthilia secunda*). The fourth group, linking the non-reclaimed site (NR100) and the youngest reclaimed one (R5), was distinguished by *Gypsophila fastigiata* and *Carlina vulgaris*, species of poor and shallow, mostly calcareous grassland. Also worth mentioning is a group of species associated mainly with the youngest (R5) and oldest (R35) reclaimed sites, represented by the orchids *Epipactis atrorubens* and *E. helleborine,* and by *Vicia cracca*. Site R15 (15-year-old afforested site) was distinguished by the presence of grassland species (*Thesium linophyllon, Asperula cynanchica, Gentianella germanica*), meadow species (*Molinia caerulea, Crepis biennis*) and forest species (*Euonymus europaea*).

Of the 27 lichen species, 13 occurred on stones and 14 on soil and dead plant remnants (Table 6). Most of them were common species connected with limestone substrate. Lichens formed three distinct groups. The first comprised species occurring at all study sites (*Verrucaria muralis, Cladonia pyxidata, C. pocillum, Vezdaea stipitata*). The second group, linking the youngest reclaimed site (R5) with the spontaneously vegetated site (NR100), comprised *Bacidia bagliettoana, Bacidina phacodes* and *Sarcosagium campestre*. The non-reclaimed site (NR100), richest in species, was distinguished from the others by the presence of *Diploschistes muscorum*.

The relation between species composition of vegetation and habitat conditions was determined using RDA (Fig. 1). The first two axes of RDA explained 23% of species variability (16% by axis 1, 7% by axis 2), and 66% of the variability included in the environmental data set was responsible for this variability. Axis 1 represented the main environmental gradient connected with the development of soil and vegetation. Moving from the right to the left side of the diagram, soil pH decreases, soil fertility increases (rise of N concentration and CEC), and exchangeable Cd increases. Species typical of alkaline, nutrient-poor soil (low C, N, P) and dry and warm habitats, such as *Gypsophila fastigiata, Scabiosa ochroleuca*, with seedlings of *Tilia cordata* and *Acer pseudoplatanus* and rock lichens (*Verrucaria muralis, Sarcosagium campestre, Bacidia bagliettoana*) are on the right side of the axis. Species requiring more fertile and wetter soils, less sunny locations,

Table 3. Factor loadings of chemical composition of soil on mine waste.

Parameter	Factor 1	Factor 2	Factor 3
PH	**-0.83**	0.35	0.1
CEC	**0.87**	-0.25	0.01
C	**0.52**	0.08	0.13
N	**0.9**	-0.17	-0.04
P	**0.85**	0.04	-0.09
K	-0.08	-0.04	**0.93**
Ca	-0.22	**0.82**	-0.41
Mg	-0.37	**0.74**	-0.18
Zn	-0.14	**0.87**	0.06
Pb	0.16	**0.79**	0.03
Cd	-0.15	**0.78**	0.37
Zn_{ex}	**0.89**	-0.14	-0.1
Cd_{ex}	**0.89**	0.03	0.16
Explained variability	39	27	10

Loadings greater than 0.50 or lower than –0.50 are given in bold; ex – exchangeable form of element.

Table 4. Species richness (S) and Shannon-Wiener diversity index (H') of field layer vegetation on reclaimed (R5, R15, R30, R35) and spontaneously vegetated (NR100) mine wastes.

Site	Vascular plant		Lichens	
	S	H'	S	H'
R5	59 ^{a}	3.37 ^{c}	12 ^{a}	1.76 ^{a}
R15	70 ^{b}	3.31 ^{c}	17 ^{ab}	2.62 ^{b}
R30	69 ^{ab}	2.87 ^{a}	21 ^{b}	2.62 ^{b}
R35	86 ^{c}	3.65 ^{d}	8 ^{a}	1.87 ^{a}
NR100	59 ^{a}	3.08 ^{b}	23 ^{b}	2.67 ^{b}

Significant differences ($p<0.05$) of indexes between sites are indicated by different letters.

and tolerating soils with high content of heavy metals are on the left site of the axis. They were represented by *Ranunculus acris, Veronica chamaedrys, Galium album* and *Pimpinella saxifraga*. The second axis was negatively correlated with potassium, an element not connected with organic matter but with the mineral fraction of the soil. Concentrated in the lower part of the axis are numerous lichens of open dry grasslands, occurring on soil, dead vascular plant remnants and moss turfs (*Cladonia* sp., *Diploschistes muscorum*) as well as on exposed stones (*Mycobilimbia tetramera, Verrucaria aethiobola*). In addition to lichens there were *Leontodon hispidus* subsp. *hastilis, Gentianella germanica, Rhinanthus minor* and *Erysimum odoratum.* On the other side of the axis are *Epipactis helleborine, Vicia cracca* and *Leontodon hispidus* subsp. *hispidus*. High concentrations of P, C and heavy metals (Zn, Cd) favored luxuriant growth of *Dianthus carthusianorum, Carex caryophyllea* and *Festuca ovina*. They are concentrated in the lower left part of the diagram. *Brachypodium pinnatum, Cerastium arvense, Carex hirta* and *Malaxis monophyllos* (upper left of diagram) occurred on more fertile and more acid soil in less sunny places. Grassland and meadow species (*Carlina vulgaris, Daucus carota, Euphrasia stricta*) occurred on shallow soil in locations that are open but slightly more favorable for the development of plants (lower right of diagram).

Discussion

Soils of Zn-Pb Mine Waste

The soils of the whole study area had similar structure and chemistry, associated with the properties of substrate that originated from mine waste (Zn-Pb ores). The waste has been weathering slowly; this accounts for the skeletal character of the originated soils, which are rich in Ca, Mg and heavy metals (Zn, Pb, Cd). The concentrations of these metals are many times higher than in natural soils of Poland [11], and comparable to the concentrations found in metalliferous soils in other Zn-Pb post-mining areas of Europe [12].

Soils originated on limestone substrate, such as those in the study area, are characterized by high pH (>7). At such high pH, most heavy metals occur in insoluble forms unavailable to plants [13]. The concentrations of total forms of metals in post-mining soils are so high that the amounts potentially available to plants are also very high. It should be added that as a rule the pH of the rhizosphere is lower than outside it; this means that the solubility/availability of metals in the rhizosphere of plants can be considerably higher. Studies by Szarek-Łukaszewska and Niklińska [14] at two post-mining sites (R30, NR100) showed that the concentrations of metals in plants growing on these soils were much higher than in plants from non-mining areas.

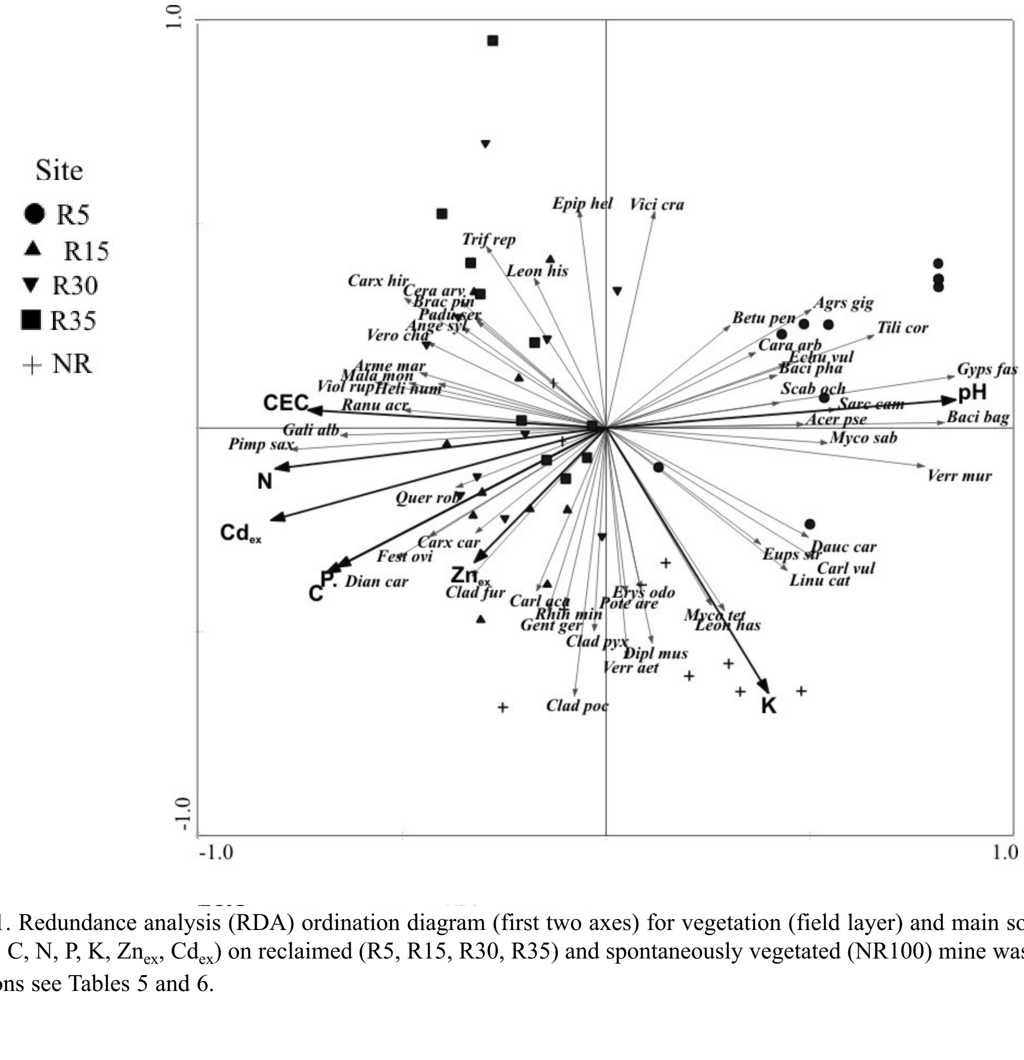

Fig. 1. Redundance analysis (RDA) ordination diagram (first two axes) for vegetation (field layer) and main soil characteristics (pH, CEC, C, N, P, K, Zn_{ex}, Cd_{ex}) on reclaimed (R5, R15, R30, R35) and spontaneously vegetated (NR100) mine waste. For species abbreviations see Tables 5 and 6.

Table 5. Results of grouping vascular plants from the reclaimed (R5, R15, R30, R35) and spontaneously vegetated (NR100) mine wastes. Groups of species are separated by thick continuous lines.

			Site																																																		Ecological indicator values			
			NR100										R5										R15										R30										R35										Light	Soil moisture	Trophy	Soil acidity
			Plot																																																					
Species	Abbr.	L	7	8	2	6	3	1	9	10	4	5	1	7	2	8	4	5	6	10	3	9	4	5	10	3	8	6	9	7	1	2	3	9	4	2	6	1	7	10	8	5	7	4	2	6	3	8	5	10	9	1				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
Trifolium medium L.	*Trif med*	C																								1					1												1			1		1					4	3-2	3	4
Quercus robur L.	*QuerrobB*	B																																									1		1	1			1			1	4	3-4	3-4	3-4
Betula pubescens Ehrh.	*Betu pub*	C																																												1		1					4	3	2-3	3-4
Dactylis glomerata L.	*Dact glo*	C																																												1			1				4	3	4-5	4-5
Poa angustifolia L.	*Poa ang*	C																												1														1	1		1				1	1	4	2-3	3	4-5
Verbascum nigrum L.	*Verb nig*	C																																										1	1		1					1	4	3	3	3-5
Medicago lupulina L.	*Medi lup*	C																																										1	1		1				1		5	2-3	3-4	3-5
Centaurea scabiosa L.	*Cent sca*	C																																										1							1		5	2-3	3	4-5
Pyrola minor L.	*Pyro min*	C																																									1				1						3	3	3	3-4
Orthilia secunda (L.) House	*Orth sec*	C																								1														1			1	1			1	1					2	3	3	3
Anthoxanthum odoratum L.	*Antx odo*	C																																									1	1	1			1					4	3	3	3
Acer platanoides L.	*Acer pla*	C																																									1					1	1		2		4	3	3-4	4
Potentilla collina Wibel	*Pote col*	C																																1		1	1								1		1			1			5	2	2	3-5
Rumex acetosella L.	*Rume acl*	C																																	1	1	1	1					1										4-5	2	2	2-3
Avenula pubescens (Huds.) Dumort.	*Aveu pub*	C																																1		1																	4	3-4	3	4-5
Taraxacum officinale F.H.Wigg.	*Tarx off*	C																																		1		1															4	3	4	4-5
Larix decidua Mill.	*LaridecA*	A														1				1													3	2	2	1	1	1	3	3	2	2	1	4	3	1	3	1	4	3	4	4	5	3	2	3
Betula pendula Roth	*BetupenA*	A	1													1										1		1					1	1	1		1	1	2	1	1	1	1	1	1	5	2	2	1		1		4	3	2-3	3-4
Alnus incana (L.) Moench	*AlnuincB*	B																																1	1	1		1		1		1	1	1	1		1	1	1	1		1	4	4	4	4
Knautia arvensis (L.) J.M.Coult.	*Knau arv*	C											1	1									1										2	1	1	1	1				1	1	1					1	1		1	1	5	3	3-4	4-5
Coronilla varia L.	*Coro var*	C																		1													1		1	1		1	1		1				1		1		1			1	5	2	3	4-5

Table 5. Continued.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
Euphorbia cyparissias L.	*Euph cyp*	C															1																1	1	1	1	1	1			1					1			1		1		5	2	3	3-5
Brachypodium pinnatum (L.) P.Beauv.	*Brac pin*	C																															1		1	1			1	1	1	1	1	1					1				5	2	2	5
Cerastium arvense L.	*Cera arv*	C																																1	1					1			1			1	1	1	1			1	5	2	2	3-5
Elymus repens (L.) Gould	*Elym rep*	C			1										1																		2		1	1	1	1				2									1	1	4	3	3-4	3-5
Galium boreale L.	*Gali bor*	C																															1	1	1		1					1	2			1					1		4	4-2	3	4-5
Angelica sylvestris L.	*Ange syl*	C																							1									1	1				1	1			1			1							4-3	4	4	4
Robinia pseudoacacia L.	*RobipseA*	A																		1															1	1						1				1		1	1			1	4	2-3	3	3-5
Euphorbia esula L.	*Euph esu*	C																															1	1		1			1		1								1				5	3	4	4-5
Larix decidua Mill.	*Lari dec*	C												1	1						2			1									1	1	1		1		1		1		1	1	1					1		1	5	3	2	3
Padus serotina (Ehrh.) Borkh.	*PaduserB*	B											1																															1	1	1	1	1			1	1	3-4	3	3	3-4
Sorbus aucuparia L. em. Hedl.	*Sorb auc*	C																		1			1	1		1																		1	1				1			1	3	3-4	3	2-4
Fraxinus excelsior L.	*FraxexcB*	B																																1			1	1	1														3	4-3	4	4
Ornithogalum umbellatum L.	*Orni umb*	C																																			1		1		1				1								5-4	3	3	3-4
Robinia pseudoacacia L.	*RobipseB*	B											1	1		1	1			1	1	1																				1	1					1	1		1		4	2-3	3	3-5
Hieracium pilosella L.	*Hier pil*	C	1	2	1																												1	1							1			1		1							5	2	2	2-5
Rumex thyrsiflorus Fingerh.	*Rume thy*	C	1	1		1			1	1			1	1		1	1	1		1				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1				1		1		1	5	2-3	3	3-5
Pinus sylvestris L.	*PinusylA*	A	4	3		2			3	1													4	4		3	3	2	3	3	4	1	2	1		1	2	1	1	1		2	4	1	1		1	4			1	1	4-5	2-4	1-3	1-5
Carex hirta L.	*Carx hir*	C	1	1	1	1	1	1													1		2	1	1		2	1	2				2	2	1	1		2		2		2	2	2	1	1	1	1	1	2	2	2	4	2-4	2-4	3-5
Veronica chamaedrys L.	*Vero cha*	C		1	1		1	1															1	1	1		1	1	1	1			1		1					1			1	1	1	1	1	1		1	1	1	4	3	4	4
Armeria maritima (Mill.) Willd.	*Arme mar*	C	1				1	1		1	1												1	1	1	1	1	1	1	1			1	1	1	1		1	1	1		1		1						1	1		5	3	3	4
Viola rupestris F.W.Schmidt	*Viol rup*	C								1														1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1					1		1	1		4	1-2	2	5-3
Padus serotina (Ehrh.) Borkh.	*Padu ser*	C																	1		1		1					1	1	1	1	1	1	1			1			1			1	1	1	1	1	1	1	1	1	1	3-4	3	3	3-4
Rumex acetosa L.	*Rume ace*	C			1		1	1			1	1	1		1		1						1				1				1	1	1					1					1	1	1	1	1	1	1	1	1	1	4	3-4	4	4

Table 5. Continued.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
Malaxis monophyllos (L.) Sw.	*Mala mon*	C								1													1	1	1	1		1			1	1		1	1					1		1	1		1	2		1	1	1	1	1	3	4	3-4	4-5
Helianthemum nummularium (L.) Mill.	*Heli num*	C		1																				1	1			1		1			1	2	1	1	2	1	1	2	2	2	1			1	1	1		1			5	2	2	3-5
Trifolium repens L.	*Trif rep*	C						1									1						1			1				1			1		1					1			1		1	1		1	1	1		1	4	3-4	4	4
Epipactis helleborine (L.) Crantz	*Epip hel*	C												1		1	1	1	1	1		1					1		1		1		1		1	1			1	1		1		1	2	2	2	1	2	1	1	1	3-3	3	3-3	4-4
Vicia cracca L.	*Vici cra*	C											1	1	1	1	1	1	1		1										1		1		1	1		1		1			1	1	1	1	1			1	1		4	3	4	4-5
Betula pendula Roth	*BetupenB*	B											2	2	2	1	2	2	1	1	1	2														1	1						1	1	1	1	1	1	1		1	1	4	3	2-3	3-4
Epipactis atrorubens (Hoffm.) Besser	*Epip atr*	C	1	1									1		1		1		1	1	1	1		1		1		1				1													1		1	1	1	1			3	2-3	3-4	5
Betula pendula Roth	*Betu pen*	C											1	1	1	1	1	1			1			1				1							1	1	1				1				1		1		1	1			4	3	2-3	3-4
Robinia pseudoacacia L.	*Robi pse*	C											1		1	1		1			1																												1		1		4	2-3	3	3-5
Tilia cordata Mill.	*Tili cor*	C											1	1	1	1	1	1			1																																3	3	4-3	4-5
Thymus pulegioides L.	*Thys pul*	C	1	1	3	2	3	2	1	1	2		2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	2	1	2	2	3	1	1	1	1	1	1	2	1	2	1	1	3	1	2	4	3-2	3	5-3
Leontodon hispidus L. subsp. *hispidus*	*Leon his*	C	1	1	1	1	1	2	1	1	1		1	2	1	2	1	1	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2		1	3	1	1	2	2	2	3	3	3	3	1	2	1	2	4	3-4	4	4
Scabiosa ochroleuca L.	*Scab och*	C	1	1	1	2	1	1	1	1	1	1	1	1	1	1	2	2	2	1	1	1	1	2	1	1	1	2	1	2	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	2	3	5-4
Pimpinella saxifraga L.	*Pimp sax*	C	1	1	1	1	2	2	1	2	1	1	1	1	1	1		1		1		1	1	2	2	2	2	2	2	2	1	2	2	2	2	2	1	2	2	2	2	1	2	2	2	1	1	1	2	2	1	2	5	2	3	5-4
Galium album Mill.	*Gali alb*	C	2	1	2	2	2	1	2	1	1		1	1	1	1					1	1	2	1	1	2	2	2	2	1	1	1	2	1	3	2	1	2	2	2	2	2	2	2	2	2	1	2	1	1	1	2	5	2	3	5
Festuca ovina L.	*Fest ovi*	C	2	3	4	3	4	4	4	3	4	4	2	2	1		2	1	1	2	2	1	3	4	4	4	3	4	3	4	4	4	5	5	5	5	5	5	5	5	5	5		3	2	1	2	1	2	3	2	3	4	2	2	3-5
Lotus corniculatus L.	*Lotu cor*	C	1	1	2	1		2	1	2	1	1	1	1	1	1	1	1	1	2			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1		1	4	3-4	4-3	3-5
Cardaminopsis arenosa (L.) Hayek	*Card are*	C			1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	4	2	3	3-5
Achillea millefolium L.	*Achi mil*	C	1	1	2	1	1	1	1	1			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1		1		1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	4	2-3	3-4	3-4
Leontodon hispidus L. subsp. *hastilis* (L.) Rchb.	*Leon has*	C	3	3	2	2	3	2	2	3	1	2	1		1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1		1			1	1	1	1	1	1	1	1	1	1	1	4	3-4	4	4
Ranunculus acris L.	*Ranu acr*	C	1	1	2	1	2	2	1	1	1			1				1				1	1	1	1	1	2	2	1	2	1	1	1	2	2	1		1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	4	3-4	4	4-5
Dianthus carthusianorum L.	*Dian car*	C	1	2	2	1	2	2	2	2	1	2		1		1	1				1		1	2	2	2	2	2	2	2	1	2		1	1	2	1	2	1		1	1	2	1	1	2	1	2	1	1	1	2	5	2	2	5-3
Pinus sylvestris L.	*PinusylB*	B	1	1	0	1	1	1	1	1	1	1	1	1	1	3	3	2	2	2	1	2	3	3	3	3	1	1	3	1	1	2	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0	0	1	1	0	4-5	2-4	1-3	1-5
Plantago lanceolata L.	*Plan lan*	C	1	1	2	1	2	2	1	1	1	1		2	1	1	1	1	1	1	1	1	1		2		2	2	2	2		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	4	2-4	3-4	4

Table 5. Continued.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
Silene vulgaris (Moench) Garcke	*Sile vul*	C	1	1	1	1	1	1			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1			1	1	1	2	1		1	1	1	1	1	1	1	1	2		1	1	4	3	3	5-4
Campanula rotundifolia L.	*Camp rot*	C	1	1	1		2	1	1	1	2							1	1	1		1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1		2	1	1	1	1	2	2	1	1	4	2-3	3	2-5
Pinus sylvestris L.	*Pinu syl*	C	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1	1			1	1	1	1	1	1	1	1	1	2	1	1			1	1			1		1	1	1	1	1	1		1		1	4-5	2-4	1-3	1-5
Anthyllis vulneraria L.	*Anty vul*	C	1	1	1	1	2	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	2	2		1	1			1	1		1		1	1	1	1	1	1		1		1	5	3	3	4
Potentilla arenaria Borkh.	*Pote are*	C	3	2	2	2	2	2	2	2	3		1	1	1	1	1	1	1	1			2	1	2	1	1	1	1	1				1		1	1	1		1		1	1	1	1	1	1		1	1		1	5	1	2-3	5
Agrostis gigantea Roth	*Agrs gig*	C	1	1		1			1	1			2	1	1	1	2	2	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1						1			1	1	2	1	1	1	1	2	1	1	4	3	3-4	3-4
Ranunculus bulbosus L.	*Ranu bul*	C	1	1	1		1	1	1	1			1	1		1			1				1		1	1	1	1	1	1			1	1	1	1		1	1			1	1		1	1		1	1	1	1		5	2-3	3	5
Quercus robur L.	*Quer rob*	C	1	1	1	1		1	1		1					1		1					1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1		1	1	1		1	1	1			1	4	3-4	3-4	3-4
Carex caryophyllea Latourr.	*Carx car*	C		1		1	1		1	1	2	1			1								1	1	1	1	1	1	1	1	1		1		1	1	1	1	1	1		1	1	1	1	1	1	1	2		1	1	4	2	2	4-5
Biscutella laevigata L.	*Bisc lae*	C	1	1	1	1	1	1	1	1	1	2	1	1	1	1			1	2	1	2	1	1	1	1	1	1	1	1	1		1	1		1	1	2	1		1		1									1	5	3	2	5
Linum catharticum L.	*Linu cat*	C	2	2	1	2	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	2		1	1	1	1	2				1	1					1		1		1				1		1	4	2-4	3	3-5
Rhinanthus minor L.	*Rhin min*	C	1	2	2	2	1	1	1	1	1	1					1						1	1	2		1	1	1	1	1		1			1	1	1			1			1		1	1			1		1	4	3-4	3	4
Carlina acaulis L.	*Carl aca*	C	1		1	1			1	1		1											1	1		1		1	1	1		1	1	1			1															1	4	2-3	3	3-5
Viola tricolor L. s.str.	*Viol tri*	C			1	1	1						1			1	1						1		1		1		1	1	1	1							1											1			5	3	3-2	3
Frangula alnus Mill.	*FranalnB*	B										1											1	1					1		1		1	1																	1		3-5	5-3	3	3
Alyssum montanum L.	*Alys mon*	C					1		1														1		1	1						1	1			1		1															5	2	2	5
Frangula alnus Mill.	*Fran aln*	C						1															1		1	1						1		1			1		1										1				3-5	5-3	3	3
Ranunculus serpens Schrank *ssp. nemorosus* (DC.) G.López	*Ranu nem*	C							1	1									1				1	1							1		1					1									1						4-5	3	3	3-4
Thesium linophyllon L.	*Thes lin*	C																					1	1	1	1	1	1			1	1																					5	2	2	5
Cornus sanguinea L.	*Corn san*	C																					1	1		1							1	1			1				1	1											3-4	2-4	4	4-5
Potentilla erecta (L.) Raeusch.	*Pote ere*	C					1																1		1		1				2								1	1					1								4	3-4	2-3	2-4
Asperula cynanchica L.	*Aspe cyn*	C																						1		1						1																					5	1-2	2	5
Juniperus communis L.	*JunicomB*	B																								1					1	1																					4	3-2	3	3-4
Molinia caerulea (L.) Moench	*Moli coe*	C																								1					1	1																					4	4-5	2-3	1-5

Table 5. Continued.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
Euonymus europaeus L.	*Euon eur*	C	1	1		1			1	1													1		1		1		1	1																							3	3-4	4	4-5
Valeriana officinalis L.	*Vale off*	C	1	1																			1	1			1		1			1																				1	3-4	4-3	4	4-5
Seseli annuum L.	*Sese ann*	C	1																				1		1		1	1	1	1	1																						5	1	2	4-5
Crepis biennis L.	*Crep bie*	C	1	1																							1		1													1			1								4	3	4	4-5
Cornus mas L.	*Corn mas*	C																									1		1																											
Gentianella germanica (Wild.) Borner	*Gent ger*	C					1			1	1	1												1	1			1						1																			5	3	3	3
Reseda lutea L.	*Rese lut*	C					1																	1																												1	5	2-3	3-4	4
Cerastium holosteoides Fr. Emend.Hyl.	*Cera hol*	C		1									1	1					1						1		1		1															1		1				1			4	3-4	3-4	3-5
Acer pseudoplatanus L.	*Acer pse*	C		1		1								1		1			1																											1						3	3-4	4	3-5
Erysimum odoratum Ehrh.	*Erys odo*	C		1		1	1	1																																												5	2	3	5
Caragana arborescens Lam.	*Cara arb*	C																	1			1																																	
Carlina vulgaris L. s. l.	*Carl vul*	C	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1		1	1			1					1		1	1																		4	2-3	3	3-5
Euphrasia stricta D.Wolff ex J.F.Lehm.	*Eups str*	C	1	1	1	1			1	1			1				1	1	1		1			1	1	1				1		1																				5	2-3	3	5-3
Gypsophila fastigiata L.	*Gyps fas*	C	1	1	1	1		1	1		1		2	2	2	3	2	2	2	2	2	2				1		1																								4	2	2	5-4
Daucus carota L.	*Dauc car*	C	1	1	1	1			1	1			1			1			1	1	1	1		1				1																								5	3	4	4-5
Larix decidua Mill.	*LaridecB*	B											1	2	2	2	2	2	1	2	1	2												1			1	1	1		1					1							5	3	2	3
Verbascum thapsus L.	*Verb tha*	C		1	1								1		1																																					5	3	3-4	4-5
Tilia cordata Mill.	*TilicorB*	B											1		1			2	1																																	3	3	4-3	4-3
Festuca pratensis Huds.	*Fest pra*	C												1	1																																					4	3	4	4
Echium vulgare L.	*Echu vul*	C															1			1	1																															5	2	3	4-5
Peucedanum ore-oselinum (L.) Moench	*Peuc ore*	C	1						1																																											4	2	2-3	2-5
Alnus glutinosa (L.) Gaertn.	*AlnugluB*	B											1																					1						1						1							3	5	3-4	4
Fraxinus excelsior L.	*Frax exc*	C																		1										1																1						3	4-3	4	4

Table 5. Continued.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
Alnus incana (L.) Moench	*Alnu inc*	C																																																	1	1	4	4	4	4
Botrychium lunaria (L.) Sw.	*Botr lun*	C																																			1												1				4	3	3	3-5
Brachypodium sylvaticum (Huds.) P.Beauv.	*Brac syl*	C																																					1					1									3	3-4	3-4	4-5
Galeopsis pubescens Bresser	*Gale pub*	C																											1															1												
Juniperus communis L.	*Juni com*	C												1																																					1		5	3	2	2
Lupinus sp.	*Lupi sp*	C																1																									1													
Poa trivialis L.	*Poa tri*	C																																				1												1			4	4	4	4
Quercus rubra L.	*Quer rub*	C														1																												1									4	3-4	3-4	3-4
Salix caprea L.	*Salx cap*	C																1						1																													5-3	3-4	4-3	3-4
Trifolium pratense L.	*Trif pra*	C	1																																					1													4	3	4	4
Viburnum opulus L.	*Vibu opu*	C																														1											1										3	3-4	3-4	4

Abbreviations for species names consist of the first four letters of the genus and the first three letters of the species; L – vegetation layer: A – tree layer, B – shrub layer, C – herb layer. Ecological indicator value – Light: 1 – deep shade (plant growing only in strongly shaded places), 2 – moderate shade (plant occurring chiefly in shaded places), 3 – half-shade (plants growing often in half–shade), 4 – moderate light (plant occurring chiefly in full light), 5 – full light (plants growing only in full light); Soil moisture: 1 – very dry, 2 – dry, 3 – fresh, 4 – moist, 5 – wet, 6 – aquatic; Soil acidity: 1 – highly acid soils, pH<4, 2 – acidic soils, 4<pH<5, 3 – moderately acidic soils, 5<pH<6, 4 – neutral soils, 6<pH<7, 5 – alkaline soils, pH>7 [after 8].

Table 6. Results of grouping lichens from reclaimed (R5, R15, R30, R35) and spontaneously vegetated (NR100) mine wastes. Groups of species are separated by thick continuous lines.

		Site																																																	
		NR100										R5										R15										R30										R35										Habitat
		Plot																																																		
Species	Abbr.	6	2	4	1	7	10	9	3	5	8	8	4	7	3	1	6	10	2	9	5	1	10	3	2	9	8	1	7	6	5	10	8	3	7	6	1	9	4	5	2	9	5	8	3	10	6	1	7	4	2	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
Cetraria aculeata (Schreb.) Fr.	*Cetr acu*		1			1			1																																											H
Mycobilimbia tetramera (De Not.) Vitik	*Myco tet*	1			1						1																																									S
Arthonia lapidicola (Taylor) Branth & Rostr.	*Arth lap*					1					1																																									S
Verrucaria nigrescens Pers.	*Verr nig*						1			1	1																	1				1					1															S
Lecanora albescens (Hoffm.) Branth & Rostr.	*Leca alb*	1			1		1			1	1								1													1																				S
Verrucaria bryoctona (Ach.) Hertel & Leuckert	*Verr bry*		1		1	1	1			1	1								1											1		1																				S
Diploschistes muscorum (Scop.) R. Sant	*Dipl mus*	1	1	1	1	1	1	1	1	1	1																																									H
Agonimia tristicula (Nyl.) Zahlbr.	*Agon tri*	1					1															1										1				1																H
Verrucaria aethiobola Wahlenb.	*Verr aet*	1		1	1	1	1		1	1																		1									1															S
Cladonia foliacea (Huds.) Willd.	*Clad fol*				1	1	1		1	1																		1	1						1	1																H
Cladonia furcata (Huds.) Schrad.	*Clad fur*		1	2		1	1	1	1	1												1						1	1	1		1		1	1	1			1	2												H
Candelariella aurella (Hoffm.) Zahlbr.	*Cand aur*										1								1									1		1								1	1													S
Cladonia pocillum (Ach.) Grognot	*Clad poc*	1	1	1	1	1	1	1	1		1				1							1						1	1	1			1		1	1	1	1		1					1							H
Cladonia pyxidata (L.) Hoffm.	*Clad pyx*	1	2	1	1	2	1	2	2	2	1		1		1				1		1	1						1	1	1		1	1		1	1	1	1	1	1	1	1		1	1	1		1	1	1		H
Verrucaria muralis Ach.	*Verr mur*	1	1	1	1	1	1	1	1	1	1	2	2	1	1	3	1	1	2	1	1	1						1	1	1		1	1		1	1	1	1	1			1		1	1	1		1	1	1		S
Mycobilimbia sabuletorum (Schreb.) Hafellner	*Myco sab*	1			1	1	1	1			1	1	1		1	1	1	1	1	1	1												1					1							1	1		1	1	1		S
Vezdaea stipitata Poelt & Dobbeler	*Vezd sti*	1			1	1			1	1		1	1		1	1		1		1		1							1									1			1	1		1	1	1		1	1	1	1	H

Table 6. Continued.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
Cladonia glauca Florke	*Clad gla*		1	1		1		1	1	1																														1				1		1			1	1		H
Bacidina phacodes (Korb.) Vezda	*Baci pha*					1							1			1		1	1	1	1	1										1			1		1													1		H
Bacidia bagliettoana (A. Massal. & De Not.) Jatta	*Baci bag*	1	1	1	1	1		1	1		1	1	1	1	2	1	1	1	2	1	1											1																				S
Sarcosagium campestre (Fr.) Poetsch & Schied.	*Sarc cam*										1	1		1			1	1		1	1																															H
Vezdaea aestivalis (Ohlert) Tscherm.- Woess & Poelt	*Vezd aes*																					1						1																								H
Physcia caesia (Hoffm.) Furnr.	*Phys cae*																					1						1																								S
Verrucaria obfuscans (Nyl.) Nyl.	*Verr obf*										1																	1								1								1						1		S
Verrucaria bryoctona (Th. Fr.) Orange	*Verr bry*																	1	1																		1															H
Cladonia fimbriata (L.) Fr.	*Clad fim*																											1							1																	H
Scoliciosporum umbrinum var. turgidum (Ach.) Arnold	*Scol umb*										1																												1													S

The basic nutrients for plants are nitrogen, phosphorus and potassium. The source of nitrogen for plants is derived almost exclusively from organic matter. Developing soils have little organic matter [15], so the nitrogen supply depends on atmospheric deposition and the presence of nitrogen-fixing microorganisms. In the study area, the youngest study site (R5) is an example of initial soil containing very little nitrogen. In the course of the development of an ecosystem the nitrogen cycle closes and the amount of nitrogen should increase in the soil. In the study area, however, the concentration of total nitrogen was still low in forest soils (R30, R35). Similar low values were reported by Alvarez et al. [16] and Shu et al. [17] from metalliferous soils of post-mining areas, and by Niklińska et al. [18] from soils of natural and artificial forests surrounding the study area. Most total nitrogen is not directly available to plants. The available nitrogen originates from processes of decomposition of organic matter and mineralization. The soil C/N ratio may be an index of the quality of these processes. For proper mineralization the C/N ratio should be about 20 [19]. In young soils this ratio is much higher, which means that all the nitrogen has been used by microorganisms [19]. In the region studied this seems to be the situation at the youngest study site (R5). After several decades, the natural development of soils in the degraded post-mining area may bring the C/N ratio to levels similar to those in soils of undisturbed sites [19]. In the investigated region the C/N ratio was low in the soils of the oldest forest site (R35), similar to values recorded from soils of forests bordering the post-mining area [18]. The high C/N ratio in the soil of the grassland (NR100) is worth noting; it may testify to a low rate of decomposition and mineralization of organic matter and to a deficiency of nitrogen for plants.

Potassium almost does not occur in organic forms in the soil; its concentrations are higher in the mineral than in the organic horizon. From the latter it is easily leached [15]. The uptake of potassium by plants may be limited in conditions of high amounts of Ca and Mg in soil solution [15]. In the soils of the investigated area the concentrations of these two elements are high, suggesting the possibility of potassium deficiency in the plants.

Plant-available phosphorus originates from minerals and organic matter [15]. The solubility of phosphorus compounds is low in alkaline soils containing high amounts of Ca and Mg, so these soils are characterized by a deficiency of plant-available phosphorus. Such soils may be colonized by plants capable of increasing the solubility of phosphorus compounds; these are calcicolous species [20] and species living in symbiosis with mycorrhizing fungi [21]. In the studied post-mining area, most plant species are mycorrhizing species [22].

As mentioned above, organic matter is the main source of nitrogen and phosphorus. These elements are often deficient in metalliferous soils such as those studied here. In addition to other factors (e.g. high pH and high Ca concentration in the case of P deficiency), a deficiency of macroelements may be caused by high concentrations of heavy metals, which slow the rate of organic matter decomposition.

Then the undecomposed organic matter accumulates, excluding part of the nutrients from the biogeochemical cycle [27]. It is the reduced activity of microorganisms (an effect of heavy metals) which is responsible for retardation of organic matter decomposition [27].

Vegetation of Zn-Pb Mine Waste

Areas created by opencast mining are bare and deprived of any biological life. Their revegetation is necessary for many reasons. Vegetation protects the ground surface against wind erosion and diminishes the threat of water erosion. There are also other obvious environmental benefits (providing habitat for animal species, carbon capture, etc.). It plays an important role in restoring or adding landscape values. It is not easy to quickly revegetate an area with unfavorable soil structure and soil chemistry, and particularly difficult to recultivate waste produced from extraction of metal ores. The time needed for dense woodland to develop spontaneously on degraded sites differs depending on soil conditions. In Central Europe it is ca. 20 years. On dry and toxic soils it may take much longer [28]. Tree planting offers quick revegetation of vast degraded areas [29]. In the investigated post-mining area, where, as shown in the present paper, habitat conditions were extremely difficult for the development of vegetation, 30 years ago several species were planted once and left without further human intervention. Currently these sites represent open woodlands with developed undergrowth and herb layer (R30, R35). This mode of reclamation is desirable if our principal aim is only to green an area, but if the area destroyed by mining activity is relatively small and there is local vegetation in its vicinity, artificial planting is unnecessary. Plant cover will develop through spontaneous colonization by local plants [2, 28, 30].

Colonization of mining areas by plants, and the rate of vegetation development, depend on which communities exist on the margin of degraded areas; they are the main source of diaspores. For the investigated younger post-mining sites, potential sources of diaspores could be the oldest (100-year-old) grassland, with species adapted to the specific conditions of mine waste, as well as small patches of grassland vegetation that have survived amidst the sites destroyed by mining activity. At the moment of its establishment, the youngest (5-year-old) site was surrounded by vegetation that had been developing for a long time (e.g. grasslands, older woodland). Species from neighboring grasslands appeared among the thinly planted trees of R5. These were vascular plants and lichens, as well as self-sowing birch, reported by Prach and Pysek [28] to be the most frequent tree in the first stages of colonization of areas degraded by human activity. It seems that after 5 years of development, vegetation cover of the mine waste might be dense enough to prevent erosion.

The supply of forest species diaspores is small in the investigated area because the forests, destroyed by many years of mining activity, are a considerable distance away. In the oldest woodlands are a few forest plants producing small seeds that are easily transported by wind, such as *Pyrola minor, Orthilia secunda* and orchids (*Epipactis helleborine, E. atrorubens*). Heavy vehicular traffic and movement of people, connected with continuing technical work, may have played an important role in the dispersion of seeds in the investigated area.

The physical and chemical properties of the waste and the soil developing on it undoubtedly determine the species composition of plants spontaneously colonizing the area. It should be emphasized that the substrate of the investigated sites varies greatly in its surface features, pH, and content of nutrients and toxic compounds. Plants there encounter a variety of microhabitats, from dry and strongly alkaline to wetter and weakly acid, with higher or lower concentrations of metals. As a result, the studied post-mining sites differed floristically. In the patches of strongly alkaline soil there were calcicolous species (*Potentilla arenaria, Galium album, Ranunculus bulbosus*); places with lower pH were overgrown by species of neutral meadows (*Pimpinella saxifraga, Rhinanthus minor*), and acid soils favored the occurrence of *Campanula rotundifolia*. Shallow soil resembling scree was the habitat for rock lichens and plant species having shallow root systems (*Gentianella germanica, Cardaminopsis arenosa*) or roots deeply penetrating the skeletal substrate (*Silene vulgaris, Biscutella laevigata*). In addition to species with specific requirements, the post-mining area harbored many species with a wide amplitude of habitat requirements (*Plantago lanceolata, Festuca ovina*). Other authors have noted similar species diversity in areas degraded by opencast mining [12, 31].

Among the vascular plants and lichens occurring in areas affected by Zn-Pb mining, one may distinguish a group of species specific to such regions: metallophytes [12, 23, 32-34]. The classic places of their occurrence in Europe are in Belgium, France and Germany. Those species are absent from the investigated area, but many common species (e.g. *Silene vulgaris, Armeria maritima, Dianthus carthusianorum*) or rare ones (e.g. *Biscutella laevigata*) show features that differentiate them from individuals growing in non-metalliferous soils [35-39]. They have been labeled metal-resistant ecotypes. These species also have ecotypes in other metalliferous areas of Europe [12, 33]. Of the lichens occurring in the investigated area, *Diploschistes muscorum* has also been found in other metalliferous areas and determined to be a hyperaccumulator of zinc [32].

Many authors have noted that trees can remain healthy and productive even under exposure to extremely high concentrations of metals in the soil, though their growth rate is lower than in uncontaminated soils [40, 41]. These researchers suggest that such tolerance may be facultative: the roots may avoid the metal-polluted places or may immobilize the metals. Developing trees may significantly affect habitat conditions. Their dense canopy reduces the amount of light reaching the ground surface and increases its moisture, which in turn enables the growth of shade-tolerant species [42]. In the investigated region, sites reclaimed by tree planting formed either open woodland (R5, R15) or denser mixed forests (R30, R35), depending on their age.

At the younger replanted sites, vegetation of a composition similar to grassland persisted in gaps between trees. At older sites, shaded to a different degree, there occurred more species typical of moderately dry to moderately humid habitats, moderately rich in nutrients. With time, as shrubs and trees develop and as shading increases in the reclaimed sites, species diversity may decline as habitat conditions become more uniform. The number of photophilous species (lichen, plants) has already decreased on a 35-year-old afforested site (R35).

In metalliferous areas, the number of species comprising grassland ranges from the under twenty to several dozen [12, 23]. Generally, grasslands developing on Zn-rich substrates are richer in species, and poorer on substrates with high concentrations of Pb. In terms of the number of species, the grasslands of the study area are similar to European zinc grasslands. The grasslands of post-mining areas often are temporarily stable communities, because heavy metals considerably retard succession [12, 23], but the grasslands are slowly overgrown by shrubs and trees. To maintain grasslands on the landscape, special measures are required to prevent the development of spontaneously germinating tree and shrub species. The natural grasslands of metalliferous areas (specific communities with valuable species) are often under protection, but the form of protection needs to be active, consisting of the removal of invading shrubs and trees. Until the 1980s the 100-year-old site (NR100) in the study area was grassland with single trees, mainly pine [24, 25]. Until the mid-20th century, goats were sporadically grazed in the area. After cessation of grazing, the development of trees was retarded by atmospheric pollution (SO_2, metallic dusts) emitted from smelting plants adjacent to the mine. When these emissions rapidly declined in the 1990s, pine trees began to multiply in the 100-year-old grassland. Currently, the pine population is expanding and its seedlings are numerous. At the beginning of the 21st century, atmospheric deposition of nitrogen increased in the investigated area, as in other parts of the country [26]; this will undoubtedly lead to eutrophication of habitats and consequent changes in the vegetation.

In summery, tree planting accelerates the development of plant cover on post-mining metalliferous areas but does not allow for maintenance of local vegetation. Permitting spontaneous development of local vegetation seems an appropriate way to rehabilitate at least part of the area. It allows islands of vegetation to persist, where species and populations typical of specific metalliferous habitats concentrate, increasing the biodiversity of post-industrial areas.

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References

1. TORDOFF G.M., BAKER A.J., WILLIS A.J. Current approaches to the revegetation and reclamation of metalliferous mine wastes. Chemosphere, **41**, 219, **2000**.
2. MARTINEZ-RUIZ C., MARRS R.H. Some factors affecting successional change on uranium mine wastes: Insights for ecological restoration. Appl. Veg. Sci., **10**, 333, **2007**.
3. WIERZBICKA M., ROSTAŃSKI A. Microevolutionary changes in ecotypes of calamine waste heap vegetation near Olkusz, Poland. A review. Acta Biol. Crac. Ser. Bot., **44**, 7, **2002**.
4. LISZKA J., ŚWIĆ E. Bolesław Mining and Smelting Works. History–facts–people. Zakłady Górniczo-Hutnicze "Bolesław", Bukowno, **2004**.
5. CARTER M.R. Soil sampling and methods of analysis. Canadian Society of Soil Science, Lewis Publisher, Ann Arbor, **1993**.
6. MIREK Z., PIĘKOŚ-MIRKOWA H., ZAJĄC A., ZAJĄC M. Flowering plants and pteridophytes of Poland. A checklist. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, **2002**.
7. BIELCZYK U. The lichens and allied fungi of the Polish Carpathians – an annotated checklist. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, **2002**.
8. ZARZYCKI K., TRZCIŃSKA-TACIK H., RÓŻAŃSKI W., SZELĄG Z., WOŁEK J., KORZENIAK U. Ecological indicator values of vascular plants of Poland. Wydawnictwo Instytutu Botaniki PAN im. W. Szafera, Kraków, **2002**.
9. WILDI O., ORLÓCI L. Numerical exploration of community patterns. SPB Academic Publishing, The Hague, **1990**.
10. LEPS J., SMILAUER P. Multivariate analysis of ecological data using CANOCO. Cambridge University Press, Cambridge, **2003**.
11. DUDKA S., The estimation of total element concentrations in surface soils of Poland.. IUNG Puławy, Seria R **293**, 1, **1992** [In Polish].
12. BROWN G. The heavy-metal vegetation of north-western mainland Europe. Bot. Jahrb. Syst., **123**, 63, **2001**.
13. PRASAD M.N.V. Heavy metal stress in plants. From molecules to ecosystems. Springer, Berlin, Tokyo, **2004**.
14. SZAREK-ŁUKASZEWSKA G., NIKLIŃSKA M. Concentration of alkaline and heavy metals in *Biscutella laevigata* L. and *Plantago lanceolata* L. growing on calamine spoils (S Poland). Acta Biol. Crac. Ser. Bot., **44**, 29, **2002**.
15. BRADY N.C., WEIL R.R. eds. Elements of the nature and properties of soils. Second edition. Pearson Prentice Hall, Upper Saddle River, New Jersey, **2004**.
16. ALVAREZ E., FERNANDEZ MARCOS M.L., VAAMONDE C., FERNANDEZ-SANJURIO M.J. Heavy metals in the dump of abandoned mine in Galicia (NW Spain) and in the spontaneously occurring vegetation. Sci. Total Environ., **313**, 185, **2003**.
17. SHU W.S., YE Z.H., ZHANG Z.O., LAN C.Y., WONG M.H. Natural colonization of plants on five lead/zinc mine tailings in Southern China. Restor. Ecol., **13**, 49, **2005**.
18. NIKLIŃSKA M., CHODAK M., LASKOWSKI R. Ecological methods for effect of soil pollution. Agencja Wydawnicza Poligrafia, Kraków, pp. 63-77, **2005** [In Polish].
19. WALI M.K. Ecological succession and the rehabilitation of disturbed terrestrial ecosystems. Plant Soil, **213**, 195, **1999**.

20. STROM L., OWEN A.G., GODBOLD D.L., JONES D.L. Organic acid behavior in a calcareous soil implications for rhizosphere nutrient cycling. Soil Biol. Biochem., **37**, 2046, **2005**.
21. SHENOY V.V., KALAGUDI G.M. Enhancing plant phosphorus use efficiency for sustainable cropping. Biotechnol. Adv., **23**, 501, **2005**.
22. PAWŁOWSKA T.E., BŁASZKOWSKI J., RUHLING A. The mycorrhizal status of plants colonizing a calamine spoil mound in southern Poland. Mycorrhiza **6**, 499, **1996**.
23. ERNST W.H.O. Schwermetallvegetation der Erde. Geobotanica selecta 5. Gustav Fischer Verlag, Stuttgart, **1974**.
24. DOBRZAŃSKA J. Flora and ecological studies on calamine flora in the district of Bolesław and Olkusz. Acta Soc. Bot. Pol., **24,** (2), 357, **1955** [In Polish].
25. GRODZIŃSKA K., KORZENIAK U., SZAREK-ŁUKASZEWSKA G., GODZIK B. Colonization of zinc mine spoils in southern Poland – preliminary studies on vegetation seed rain, and seed bank. Fragm. Flor. Geobot., **45,** (1-2), 123, **2000**.
26. MILL W. Dynamic modelling of Polish forest soil response to changes in atmospheric acid deposition. Environment Protection Engineering, Wroclaw University of Technology Press, **3**, 39, **2007**.
27. BERG B., LASKOWSKI R. Litter decomposition. A guide to carbon and nutrient turnover, Ecol. Res. pp. 38, **2006**.
28. PRACH K., PYSEK P. Using spontaneous succession for restoration of human-disturbed habitats. Experience from Central Europe, Ecol. Eng., **17**, 55, **2001**.
29. SINGH A.N., RAGHUBANSHI A.S., SINGH, J.S. Plantation as a tool for mine spoil restoration. Current Sci., **82,** (12), 1436, **2002**.
30. MARRS R.H., BRADSHOW A.D. Primary succession on man-made wastes. The importance of resource acquisition. In: Primary succession on land, Miles J., Walton D.W.H. (eds.). Special Publication number f the British Ecological Society, Blackwell Scientific Publications, London,Vienna, pp. 221-248, **1993**.
31. KOMPAŁA-BĄBA A., BŁOŃSKA A., BĄBA W., CZYBA M. Grasses in plant communities which develop on the waste sites of zinc-lead industry (Upper Silesia, S Poland). In: Biology of grasses, Frey, L. (ed.). W.Szafer Institute of Botany, Polish Academy of Sciences, Kraków, pp. 269-281, **2005**.
32. CUNY D., DENAYER F.O., DE FOUCAULT B., SCHUMACKER R., COLEIN P., VAN HALUWYN C. Pattern of metal soil contamination and changes in terrestrial cryptogamic communities. Environ. Pollut., **129**, 289, **2004**.
33. ERNST W.H.D., KNOLLE F., KRATZ S., SCHNUNG E. Aspects of ecotoxicology and heavy metals in Harz region – a guided excursion. Landbauforschung Volkendrode **2**, 53, **2004**.
34. PURVIS O.W., HALLS C. A review of lichens in metal-enriched environment. Lichenologist, **28**, 571, **1996**.
35. OLKO A., ABRATOWSKA A., ŻYŁKOWSKA J., WIERZBICKA M., TUKIENDORF A. *Armeria maritima* from a calamine heap. Initial studies on physiologic-metabolic adaptations to metal-enriched soil. Ecotoxicol. Environ. Saf., **69**, 209, **2008**.
36. SZAREK-ŁUKASZEWSKA G., SŁYSZ A., WIERZBICKA M. The response of *Armeria maritima* (Mill.) to Cd, Zn and Pb. Acta Biol. Crac. Ser. Bot., **46**, 19, **2004**.
37. WIERZBICKA M., PANUFNIK D. The adaptation of *Silene vulgaris* to the growth on a calamine waste heap (S Poland). Environ. Pollut., **101**, 415, **1998**.
38. WIERZBICKA M., PIELICHOWSKA M. Adaptation of *Biscutella laevigata* L., a metal hyperaccumulator, to growth on a zinc-lead waste heap in southern Poland. I: Differences between waste-heap and mountain populations. Chemosphere, **54**, 1663, **2004**.
39. ZAŁĘCKA R., WIERZBICKA M. The adaptation of *Dianthus carthusianorum* L. (Caryophyllaceae) to growth on a zinc-lead heap in southern Poland. Plant Soil, **246**, 249, **2002**.
40. DICKINSON N. M. Strategies for sustainable woodland on contaminated soils. Chemosphere, **41**, 259, **2000**.
41. PULFORD I.D., WATSON C. Phytoremediation of heavy metal-contaminated land by trees – a review. Environ. Int., **29**, 529, **2003**.
42. AUGUSTO L., RANGER J., BINKLEY D., ROTHE A. Impact of several common tree species of European temperate forests on soil fertility. Ann. For. Sci. **59**, 233, **2002**.