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Physicochemical and biological properties of soils in the prevailing types of plant communities in the Olkusz mining region

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Introduction

Over the past decades, several soil studies have been conducted in the mining areas of Olkusz, Bolesław and Bukowno, located between Katowice and Kraków in southern Poland (e.g. Gruszczyński *et al.* 1990; Kucharski and Marchwińska 1990; Trafas *et al.* 1990; Verner *et al.* 1996; Krzaklewski *et al.* 2004; Pasieczna and Lis 2008; Cabala *et al.* 2009a). These assessments were mainly focused on the degree of heavy metal contamination. Such studies are important for several reasons. Firstly, information regarding the sites of ore extraction and disposal of mining waste is incomplete. Documentation of the mining activities generally lacks information regarding the locations of historical (i.e. more than 100 years old) ore exploitation and processing, which left minor traces on the landscape. Secondly, particle-bound heavy metals in the flue gas dust from metallurgy, as well as from wind erosion of mining waste, can be transported beyond the area of mining in quantities that are difficult to estimate. Thirdly, a large part of the population in the densely populated Olkusz region is exposed to elevated levels of heavy metals in the local environment. Despite ready access to information documenting the level of soil contamination and recommendations for its management, some of the land is used for growing fruit and vegetables, such as in small-scale backyard gardens. Moreover, gathering of wild fruit, berries and mushrooms on the post-industrial wastelands is also a common practice.

The oldest studies on the effects of industrial activity on soils of the Olkusz region date to the 1970s and 1980s. That work presents the level, range and spatial variability of heavy metal concentrations, and an evaluation of the environmental risk associated with the contamination (Trafas *et al.* 1990). Generally, research on heavy metal contamination in this region has focused on cultivated soils, due to the potential risk of human uptake through production of crops. A large number of studies provide a thorough overview of the contamination of topsoils, giving an idea of the magnitude of the problem. Practically all agricultural land in districts associated with the mining industry (i.e. Olkusz, Bukowno, Sławków and Klucze – according to the administrative division of the time) have elevated levels of cadmium, lead and zinc (Kucharski and Marchwińska 1990). This contamination renders about 13,000 hectares of agricultural land unsuited for growing traditional crops. The highest concentrations of heavy metals were found in soils developed on mining gangue in the vicinity of the Bolesław Mining and Metallurgical Plant (ZGH Bolesław), a major point source of heavy metal pollutants in the region. This area is designated as a buffer zone, within which settlement and agricultural activities are prohibited. For the less contaminated sites, sound recommendations on how to manage the soil are established and disseminated to the public.

In the early 1990s the environmental studies were relatively detailed though mainly focused on the most impacted regions close to the emission sources. With the awareness of the effect of advective air transport of heavy metals associated with dust from flue gas emissions and wind erosion of tailings ponds (e.g. Krzaklewski and Pietrzykowski 2002; Krzaklewski *et al*. 2004) attention was shifted more towards the remote forests and urban/industrial wastelands (e.g. Cabala and Teper 2007; Cabala *et al*. 2008). Not only was the content of heavy metals in the soils analysed, but also the origin, migration routes and bioavailability of heavy metals, and their interaction with other soil properties (e.g. Cabala *et al*. 2009b, 2010). This biogeochemical approach was also applied in the research within the framework of EEA FM project PL0265 in 2008–2011. The aim of this interdisciplinary study was to provide a complete description of edaphic conditions prevailing in the thoroughly studied mining area (including both areas degraded geomechanically and/or chemically).

The compiled data, presented in this chapter, constitutes the basis for explaining the variation of biodiversity and composition in the unique plant communities formed spontaneously or planted in metalliferous habitats (one of the main aims of the project; Kapusta and Godzik – Chapter 6, this volume). The EEA studies covered a large area and spanned the dominant substrate types, land uses and types of vegetation cover. Using this dataset as a reference enabled us to review the data collected in the past and thereby compare sites which have so far only been studied separately, at different times and by different authors. Moreover, the soils of this region were for the first time analysed not only in terms of their physicochemical properties but also in terms of biological characteristics, such as microbial activity and soil mesofauna, in conjunction with the characteristics of plant communities (species richness and composition).

Materials and methods

Land use in the study area is divided into three main categories: (1) mining wasteland, that is, areas transformed by opencast exploitation and processing of metal ores (generally consisting of reclaimed mining areas and post-flotation waste heaps, as well as excavations filled with such waste), where the soils are generally young and weakly developed regosols; (2) agricultural land abandoned due to heavy-metal contamination, with brown soils; and (3) afforested areas with podsols. The soil study sites ($N = 49$) are distributed among these land-use categories. The main plant communities in the mining wasteland are thermophilous grasslands (GW, $N = 7$) and grasslands dominated by *Molinia caerulea* (MW, $N = 6$), as well as some pine forests (FW, N = 6). Growing on the abandoned agricultural soil we find thermophilous grasslands dominated by *Festuca ovina* (GS, N = 7) and more mesophilous grasslands (P, N = 8). The forested areas are dominated by pine trees growing on sandy soil (FS, N = 15) (Kapusta and Godzik – Chapter 6, this volume).

Soil samples used to characterise the studied habitats were selected from one of 9 plots (usually the central plot) established within each of the study sites (Kapusta and Godzik – Chapter 6, this volume). Soil samples from 2 or 3 genetic horizons were collected using a metal shovel from 3 shallow (to 50 cm depth) pits. The organic horizon (O) was disregarded as it occurred at only a few of the examined sites; in plots where it was present it was gently removed before soil sampling. In most cases the samples were collected only from the topsoil horizon (usually A, Ap or AB) and the subsoil horizons (usually AB or B). In addition, the eluvial horizon (E, AE) was sampled in the few soil plots with podsols. Efforts were made to collect soil from the whole genetic horizon. Three soil samples from each horizon were bulked into one sample (ca. 1 kg). This reduced the variability resulting from heterogeneity of the soil environment, producing a relatively representative sample for each plot. Separate soil samples were collected for analysis of soil mesofauna from all 9 plots at each of the study sites. These samples were taken from the upper layer of the soil to a depth of 13 cm using a soil corer (3.5 cm in diameter). The soil samples were transported to the laboratory in polyethylene bags and stored at low temperature (ca. 5°C) until analysed.

Soil samples used for physicochemical characterisation were first air-dried and sieved through a 2 mm sieve. These samples were analysed for the following parameters:, soil pH and the concentrations of nutrients (carbon, C; nitrogen, N; sulfur, S; phosphorus, P; potassium, K), major cations (calcium, Ca; magnesium, Mg), minor cations (iron, Fe; manganese, Mn) and the main heavy metals (cadmium, Cd; lead, Pb; zinc, Zn). The particle size distribution of the soil (percentage fractions of sand, silt and clay) was determined using the method of sieving and sedimentation (ISO11277, 2009). Soil pH was measured in aqueous suspension (ISO10390, 1994) using a Mettler Toledo MO 125 pH-meter. Content of total and organic C and of total S was determined by dry combustion technique (ISO10694, 1995) with a LECO SC-144DRPC analyser. The concentrations of total N were determined by the Kjeldahl method (ISO11261, 1995) using a Kjeltec 2300. The total concentrations of P as well as the concentrations of metal ions – exchangeable (K, Ca, Mg, Fe, Mn, Cd, Pb, Zn) and water-soluble (Zn, Cd, Pb) fractions – were determined by flame atomic absorption spectrometry (F-AAS) with a Varian 220 FS. Total concentrations of metals in soil samples were determined after digestion using concentrated $HClO_4$. Exchangeable and water-soluble fractions were analysed in solution obtained by extraction of the soil with 1M $BaCl_2$ solution (ISO11260, 1994) and with deionised water, respectively. Content of bioavailable P was determined colorimetrically (Hach Lange DR 3800) in solution obtained by extraction of soil with sodium bicarbonate (Olsen *et al*. 1954).

The activities of soil mesofauna were analysed in random order. Animals were extracted from the soil by the wet funnel method (O'Connor 1955), heating the soil samples with lamps to shorten the time of extraction (to 5 h). The method was originally designed to extract *Enchytraeidae* worms but can also be used for rough assessment of the activity of other groups of small, mobile soil invertebrates such as nematodes (*Nematoda*) and tardigrades (*Tardigrada*). Numbers of individuals were counted using a binocular microscope. Data obtained from the nine plots at each site were averaged to obtain a representative value for each study site.

Prior to statistical analysis the variables were transformed using a logarithmic or exponential function and expressed on a 0–1 scale in order to obtain normal or at least symmetric distributions and homogeneity of variance (Økland 2007). One-way ANOVA was used to analyse the significance of differences in the mean values of the variables from the 49 topsoil horizons between the six habitat categories (GW, GS, FW, FS, MW, P). Two-way ANOVA with repeated measurements was used to assess the significance of effects of land-use type (mining wasteland, former agricultural land, afforested area) and genetic soil horizon (topsoil, subsequent layer), as well as the effect of interaction between these two factors. The analysis included only study sites (N = 40) that were clearly classified into one of the three land use categories, and where at least 2 soil horizons were analysed. Factor analysis was performed for selected physical and chemical parameters of the topsoil (for which the transformation had a positive effect) in order to determine the structure of the inter-correlations between the parameters. For extraction of principal components, the factor structure was Varimax-rotated and the number of factors was determined according to Kaiser's criterion (eigenvalue > 1). The identified factors were used as explanatory variables in a multiple regression model explaining the variation in biological parameters and plant communities (plant species richness and composition). Plant species composition was represented by variables obtained in detrended correspondence analysis (DCA), which identified major environmental gradients determining the distribution of plants (DCA axes 1 and 2). The analysis included species that occurred in at least 10% of the study sites. Statistical analyses were performed using Statistica 9, while CANOCO 4.5 was used for multivariate DCA analysis.

Results and discussion

Most of the soil physicochemical parameters were characterised by high variability both between and within habitat categories (coefficient of variation often exceeded 100%). The parameters that varied the most were the total concentrations of heavy metals, some nutrient elements (e.g. N), major cations (Ca, Mg) and exchangeable metals (Table 1). A large range of soil characteristics was expected, as this had been the goal of the sampling strategy, which selected strongly contrasting habitats. Moreover, soil characteristics within a habitat category often differed markedly due to the strong anthropogenic impacts; for example, soil material was derived from different types of mining waste, the distance from the main sources of dust pollution (smelters, tailing ponds) varied, and different plantings of vegetation influenced the degree of soil development.

The chemical analyses confirmed findings from previous studies that the soils in the studied region are extremely polluted. The highest total concentrations of heavy metals were recorded at sites established on mining wasteland: 506 mg Cd kg^{-1} and 72,089 mg Zn kg^{-1} found in a calamine grassland (GW), and 33,178 Pb mg kg^{-1} found in a meadow (MW) (Table 1). In the least polluted forested sites on sandy soil (FS) the heavy metal concentrations were about two or three orders of magnitude lower than the maximum values (2 mg Cd kg^{-1}, 93 mg Pb kg^{-1}, 132 mg Zn kg^{-1}). These latter values are within or below the range of concentrations considered under Directive

Table 1. Descriptive statistics for the physical, chemical and biological properties of topsoil, and plant species richness at the 49 study sites

Tabela 1. Statystyki opisowe właściwości fizycznych, chemicznych i biologicznych górnej warstwy gleby oraz bogactwa gatunkowego zbiorowisk roślinnych dla 49 powierzchni badawczych

Variable Zmienna	Min. Min.	Lower quartile Dolny kwartyl	Median Mediana	Mean (SD) Średnia (SD)	Upper quartile Górny kwartyl	Max. Maks.
Sand / Piasek (%)	78	89	91	91 (4)	94	98
Silt / Pył (%)	1	3	4	4 (2)	5	9
Clay / Ił (%)	1	3	5	5 (3)	6	19
pH	5.0	6.4	7.0	6.8 (0.7)	7.2	8.2
C_T (%)	0.5	1.1	2.3	3.4 (3.2)	5.0	15.2
C_{ORG} (%)	0.2	0.7	1.1	1.9 (1.9)	1.8	7.9
N_T (%)	0.03	0.08	0.13	0.20 (0.20)	0.19	0.86
S_T (%)	0.001	0.014	0.026	0.086 (0.137)	0.106	0.694
P_T (mg kg^{-1})	84	236	424	428 (254)	556	1232
P_{OLS} (mg kg^{-1})	0.6	3.1	4.0	6.2 (5.2)	7.5	23.0
K_T (mg kg^{-1})	164	365	720	763 (491)	1017	2373
Ca_T (mg kg^{-1})	91	1423	3534	10422 (13327)	16600	52398
Mg_T (mg kg^{-1})	67	458	1511	4074 (5787)	4615	19356
Fe_T (mg kg^{-1})	1326	4032	11210	16595 (16271)	25751	60632
Mn_T (mg kg^{-1})	22	168	867	842 (762)	1259	3625
Cd_T (mg kg^{-1})	2	10	25	76 (114)	88	506
Pb_T (mg kg^{-1})	93	328	843	3657 (7032)	3669	33178
Zn_T (mg kg^{-1})	132	1147	2451	9764 (15170)	12900	72089
K_{EX} (mg kg^{-1})	2	8	30	55 (60)	79	270
Ca_{EX} (mg kg^{-1})	17	311	1198	1320 (1198)	2078	4518
Mg_{EX} (mg kg^{-1})	3	33	145	210 (211)	316	861
Cd_{EX} (mg kg^{-1})	0.1	1.3	3.7	8.5 (13.5)	6.4	60.5
Pb_{EX} (mg kg^{-1})	0	0	0	4.2 (10.3)	2.6	57.0
Zn_{EX} (mg kg^{-1})	7	24	54	124 (173)	115	772
Cd_W (mg kg^{-1})	0.003	0.009	0.016	0.025 (0.030)	0.029	0.154
Pb_W (mg kg^{-1})	0.013	0.101	0.185	0.246 (0.208)	0.305	0.938
Zn_W (mg kg^{-1})	0.6	2.7	3.6	4.2 (2.4)	4.9	11.0
Number of enchytraeids (ind. m^{-2}) Liczba wazonkowców (osob. m^{-2})	0	827	2009	5537 (8453)	5554	46678
Number of nematodes (ind. sample^{-1}) Liczba nicieni (osob. próba $^{-1}$)	45	123	167	184 (105)	222	556
Number of tardigrades (ind. sample^{-1}) Liczba niesporczaków (osob. próba $^{-1}$)	0	1	5	12 (19)	11	86
Plant species richness (species plot^{-1}) Bogactwo gatunkowe roślin (gat. poletko^{-1})	2	6	11	11 (6)	16	25

Abbreviations: SD – standard deviation, $_T$ – total, $_{ORG}$ – organic, $_{OLS}$ – Olsen, $_{EX}$ – exchangeable, $_W$ – water-soluble, ind. – individual

Objaśnienia skrótów: Odch. stand. – odchylenie standardowe; $_T$ – całkowity; $_{ORG}$ – organiczny; $_{OLS}$ – Olsena; $_{EX}$ – wymienny; $_W$ – rozpuszczalny w wodzie; ind. – individual

86/278/EEC of the European Council to be the maximum permissible concentrations: 1–3 mg kg^{-1} for Cd, 50–300 mg kg^{-1} for Pb and 150–300 mg kg^{-1} for Zn (Anonymous 1986). The lower quartiles for heavy metal concentrations at all sites are higher than these limits (Table 1). This means that the levels of heavy metals in the majority of samples exceed the threshold values.

Verner *et al.* (1996) found similar levels of heavy metals in a study of soils near the Bolesław Mining and Metallurgical Plant (ZGH Bolesław). Part of their samples were collected from the same locations sampled in the current study, including abandoned agricultural land. The median total concentrations in the 10 cm topsoil layer were found by Verner *et al.* (1996) to be 14.8 mg Cd kg^{-1}, 545 mg Pb kg^{-1} and 2175 mg Zn kg^{-1}. Cabala *et al.* (2009a) surveyed a slightly different area in the vicinity of ZGH Bolesław, including sites of ore extraction and mining waste disposal (equivalent to the GW, FW and/or MW categories in this study), as well as sites affected only by dust pollution (which may resemble the FS category). The order of magnitude of their reported ranges of total concentrations of Cd, Pb and Zn (2–220 mg kg^{-1}, 172–8262 mg kg^{-1} and 378–55,506 mg kg^{-1} respectively) does not differ from the levels found in the present study (Table 1). An area corresponding to the FS sites was studied by Krzaklewski *et al.* (2004). That study was aimed at assessing the impact of dust from wind erosion of tailings ponds on the near environment. Their results were also in accord with those presented in this chapter. All the above cited findings concerning the level of soil contamination at various locations of the mining area have also been verified by recent environmental studies (Pasieczna and Lis 2008; Fabijańczyk and Zawadzki 2012; Zawadzki and Fabijańczyk 2013).

The mining waste (gangue) is a mixture of mainly crushed dolomite and calcite (Cabala and Teper 2007). Soils developed in this easily weatherable material therefore contain ample amounts of the nutrient K, as well as the major cations Ca and Mg. In situ weathering of carbonate minerals gives the soils a relatively high pH and a more favourable proportion of clay as compared to fluvial-deposited sandy soils. These soil characteristics favour the persistence of heavy metals in their insoluble forms, unavailable to living organisms (Ernst 1996; van Gestel 2008; Smolders *et al.* 2009). That is why, despite being heavily loaded with heavy metals, the soils developed on mining waste material may offer relatively good conditions for plants (Grodzińska *et al.* 2010; Szarek-Łukaszewska and Grodzińska 2011), soil microflora (Stefanowicz – Chapter 14, this volume) and mesofauna. This has been confirmed by other authors, including those studying vegetation in zinc- and lead-contaminated areas. These studies used the Pb/Ca or Za/Ca ratio (indirectly informing about the availability of Pb and Zn) as an indicator of soil toxicity, instead of the total content of heavy metals (Brown and Brinkmann 1992; Brown 1994). The soils in the calamine grasslands (GW), pine forests (FW) and meadow wastelands (MW) described in this chapter had very high content of heavy metals, though only a small fraction of this was in water-soluble and exchangeable forms (Table 2). As a result, the relative bioavailability of heavy metals (expressed as the ratio of mobile to total forms) was lower in these highly contaminated sites than in the slightly contaminated and more acid forested sandy sites (FS). Taking into account the low content of organic matter and nutrient elements (Table 2), the sandy sites of the mining area (especially GS) are considered to be the least advantageous habitat for living organisms. Studies of soil biological activity and vegetation confirm that

Table 2. Average values of variables (from Table 1) for six land-use categories

Tabela 2. Średnie wartości zmiennych (z Tabeli 1) dla sześć kategorii siedliskowych

Variable / Zmienna	GW (N = 7)	MW (N = 6)	FW (N = 6)	P (N = 8)	GS (N = 7)	FS (N = 15)
Sand / Piasek	89	92	90	89	91	94
Silt / Pył	5	3	3	5	5	3
Clay / Ił	6	5	7	6	3	3
pH	7.5^{a}	$6.9^{a,b}$	7.4^{a}	7.0^{a}	$6.7^{a,b}$	6.1^{b}
C_T	8.1^{a}	5.8^{a}	$5.2^{a,b}$	$2.0^{b,c}$	1.4^{c}	1.3^{c}
C_{ORG}*	4.0	3.0	2.7	1.2	0.9	0.8
N_T	0.38	0.30	0.22	0.16	0.11	0.13
S_T	0.220^{a}	$0.090^{a,b}$	$0.124^{a,b}$	0.021^{b}	$0.047^{a,b}$	0.059^{b}
P_T	719^{a}	$478^{a,b}$	$391^{a,b}$	531^{a}	$467^{a,b}$	213^{b}
P_{OLS}*	$4.9^{a,b}$	3.5^{a}	$5.5^{a,b}$	11.4^{b}	$10.3^{a,b}$	3.3^{a}
K_T	1596^{a}	760^{b}	865^{b}	935^{b}	623^{b}	308^{c}
Ca_T	27411^{a}	$10140^{a,b}$	$22275^{a,d}$	$10406^{c,b,d}$	$3125^{c,b,e}$	1278^{e}
Mg_T	9996^{a}	$3746^{a,b}$	8733^{a}	$4307^{a,b}$	$1653^{a,b}$	583^{b}
Fe_T	32755^{a}	25952^{a}	28255^{a}	$11922^{a,b}$	$13305^{a,b}$	4675^{b}
Mn_T*	1697^{a}	$944^{a,b}$	1080^{a}	1075^{a}	$792^{a,b}$	204^{b}
Cd_T*	192^{a}	$139^{a,b}$	149^{a}	$22^{a,b}$	$47^{a,b}$	12^{b}
Pb_T*	7012^{a}	$8250^{a,b}$	$3446^{a,b}$	$672^{a,b}$	$6290^{a,b}$	703^{b}
Zn_T	24519^{a}	19296^{a}	16653^{a}	$3063^{a,b}$	$6561^{a,b}$	1378^{b}
K_{EX}	109^{a}	$34^{a,b}$	$62^{a,b}$	105^{a}	$42^{a,b}$	14^{b}
Ca_{EX}*	2769^{a}	$1355^{a,b}$	$1489^{a,b}$	1820^{a}	$1105^{a,b}$	394^{b}
Mg_{EX}*	424^{a}	$277^{a,b}$	$182^{a,b}$	322^{a}	$124^{a,b}$	76^{b}
Cd_{EX}*	25.1^{a}	$9.8^{a,b}$	$8.3^{a,b}$	$4.0^{a,b}$	$9.9^{a,b}$	2.1^{b}
Pb_{EX}*	2.1	6.0	0	0	5.1	7.8
Zn_{EX}	256	155	140	63	193	45
Cd_W	0.044	0.043	0.022	0.018	0.016	0.018
Pb_W	$0.232^{a,b}$	$0.234^{a,b}$	0.477^{a}	0.161^{b}	$0.177^{a,b}$	$0.241^{a,b}$
Zn_W	4.8	4.5	6.4	3.0	3.9	3.7
Number of enchytraeids Liczba wazonkowców	$3849^{a,b}$	$4451^{a,b}$	$4687^{a,b}$	14550^{a}	928^{b}	$4443^{a,b}$
Number of nematodes Liczba nicieni	$179^{a,b}$	$147^{a,b}$	$219^{a,b}$	319^{a}	$166^{a,b}$	122^{b}
Number of tardigrades Liczba niesporczaków	$12^{a,b}$	$17^{a,b}$	$9^{a,b}$	36^{a}	2^{b}	4^{b}
Plant species richness Bogactwo gatunkowe roślin	15^{a}	$9^{a,b}$	16^{a}	15^{a}	5^{b}	8^{b}

Abbreviations as in Table 1; habitat category codes explained in text; nonparametric Kruskal-Wallis test was used for asterisked variables due to violation of the assumptions of analysis of variance (normality, homogeneity); other variables (transformed) were analysed by one-way ANOVA; means bearing different letters within row differ significantly (post-hoc test, $p < 0.05$)

Skróty stosowane w nazwach zmiennych objaśniono w Tabeli 1; kody kategorii siedliskowych objaśniono w tekście; gwiazdka (*) przy nazwach zmiennych oznacza użycie testu nieparametrycznego (Kruskala-Wallisa) z uwagi na niespełnione założenia analizy wariancji; pozostałe zmienne (transformowane) analizowano przy pomocy jednoczynnikowej analizy wariancji; istotne różnice (wykryte w teście post-hoc; $p < 0.05$) pomiędzy średnimi oznaczono literami; wartości nieposiadające w wierszu wspólnej litery istotnie różnią się od siebie this indeed is the case (Grodzińska *et al*. 2010; Szarek-Łukaszewska and Grodzińska 2011; Stefanowicz – Chapter 14, this volume). Wasteland sites (GW, MW, FW) have higher plant biodiversity and relatively more abundant soil invertebrate communities (enchytraeids, nematodes and tardigrades, Table 2). In this respect they are outweighed only by the old fields (P), with relatively weakly contaminated fertile soils. By contrast, the sandy sites (GS and FS) are characterised by low biological activity in the soil and low biodiversity (in extreme cases there is only one species – *Festuca ovina* – at these sites).

The characteristics described so far regarded only the upper mineral soil layer (topsoil A or AB horizon). Study of the deeper soil horizons allows an assessment of the genesis and nature of the heavy metals and soils in the area of Olkusz. Soils on mining waste (mainly GW and FW sites) are weakly developed regosols, as it is only a few tens of years since the material was deposited at the site. The topsoil is therefore poorly developed and usually does not exceed 10 cm. Moreover, it contains less heavy metals than the layer lying below (Table 3). This implies that the main source of contamination is the soil material of mining waste. In the other land use types the topsoil is much thicker and found to be more enriched in heavy metals than the underlying soil horizon (Table 3). This is thus due to accumulation of heavy metals in the topsoil, mainly from smelter emissions and from deposition of contaminated dust from wind erosion of tailings ponds and waste heaps. The natural bedrock probably also contains relatively low amounts of heavy metals, not a significant source of contamination to the deeper soil layers. The level of contamination of these topsoils is therefore mainly determined by the distance from the point sources. Vegetation cover may also play an important role, as trees limit advective transport of pollutants. Forests (FS), mainly located at some distance from the sources of heavy metal contamination, are thus much less loaded with heavy metals than the former arable fields (GS) near the smelter (Table 2).

The habitats of grassland on abandoned agricultural land (GS, P) differ substantially in terms of the physical, chemical and biological properties of the soil. This causes large differences in plant species richness (Table 2). The classification as abandoned agricultural land is based on archival data (maps) on soil types and land uses in the 1970s around ZGH Bolesław. According to these data, the GS and P sites were arable fields with brown soils. The former land use was confirmed by field observations of a deep homogeneous plough layer (Ap), clearly distinguishable from the lower B horizon. These Ap horizons had the highest levels of bioavailable and total phosphorous (Table 2), which indicates fertilisation in the past.

Pine forest on sand (FS) was distinguished as a separate habitat mainly due to its low soil pH (Table 2). This pH would likely be even lower had it not been for the effect of large deposition of alkaline dust from the smelter and wind erosion of tailings ponds and waste heaps. Heavy metals deposited on the soil adsorbed to the dust, came in contact with acidic soil solution, and were mobilised (becoming potentially more bioavailable). This is clearly reflected in the elevated levels of exchangeable Pb in the FS soils as compared to the other habitat categories (Table 2). Also, the concentration of Pb is higher in the subsoil than in the topsoil, which may reflect efficient transport of Pb (as well as Cd and Zn) down through the soil podsol profile (Table 3).

Factor analysis reduced the 25 physicochemical properties of the soil (including only variables with a normal distribution after transformation) to 5 factors explaining

Table 3. Physical and chemical properties (means) for the two soil horizons

Tabela 3. Właściwości fizyczne i chemiczne (wartości średnie) dwóch poziomów glebowych

Variable Zmienna	Mining wasteland Nieużytki górnicze (N = 15)		Abandoned arable field Tereny porolne (N = 12)		Afforested area Tereny leśne (N = 13)		Ut	Pg	Ut × Pg
	I	II	I	II	I	II			
Sand / Piasek	91	89	90	89	94	95	***	-	-
Silt / Pył	3	5	5	5	3	2	**	-	**
Clay / Ił	6	6	5	7	3	3	***	-	-
pH	7.2	7.7	7	7.4	5.9	6.1	***	***	**
C_T	6.6	4.2	1.8	1.2	1.2	0.4	***	***	-
C_{ORG}	3.6	0.8	1.1	0.4	0.8	0.2	***	***	-
N_T	0.33	0.11	0.15	0.11	0.14	0.03	***	***	-
S_T	0.173	0.026	0.03	0.006	0.063	0.004	n.a.	n.a.	n.a.
P_T	540	605	530	287	192	167	***	***	-
P_{OLS}	5	4.3	10.6	5.1	2.5	3.7	***	-	**
K_T	1057	1257	852	1195	295	248	***	-	-
Ca_T	18290	35564	8358	18298	1165	11612	***	-	-
Mg_T	6248	8632	3631	7115	552	2421	***	-	-
Fe_T	28293	42004	13661	16125	4466	4088	***	-	-
Mn_T	1185	1670	1111	1067	190	271	n.a.	n.a.	n.a.
Cd_T	158	187	33	24	11	13	***	***	**
Pb_T	6790	14058	3690	535	613	203	***	***	***
Zn_T	20595	28944	4624	4254	1310	2685	***	*	**
K_{EX}	75	55	90	51	12	13	***	-	*
Ca_{EX}	2124	1892	1810	1388	349	349	***	-	-
Mg_{EX}	351	327	279	244	55	45	***	-	-
Cd_{EX}	18.4	7.4	8	4	2	3.7	**	-	***
Pb_{EX}	5.1	2.1	0.8	0	9	18.1	n.a.	n.a.	n.a.
Zn_{EX}	235	77	138	94	44	158	-	-	***
Cd_W	0.039	0.026	0.016	0.01	0.017	0.006	**	***	**
Pb_W	0.33	0.171	0.132	0.042	0.233	0.212	***	**	-
Zn_W	5.8	3.4	3.2	1.4	3.6	1.5	***	***	-

Abbreviations as in Table 1; I – topsoil; II – subsoil; last three columns indicate the significance of the effects of Ut (land use), Pg (soil horizon) and Ut × Pg (interaction of the factors) on the physicochemical properties of soil; n.a. – effects unexamined due to violation of the assumptions of the analysis of variance (normality, homogeneity); other variables (transformed) were analysed by two-way repeated-measures ANOVA; statistical significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Skróty stosowane w nazwach zmiennych objaśniono w Tabeli 1; I – górny poziom glebowy; II – dolny poziom glebowy; ostatnie 3 kolumny zawierają informację o istotności wpływu Ut (czynnika użytkowania terenu), Pg (czynnika poziomu glebowego) oraz Ut × Pg (interakcji czynników) na właściwości fizyczne i chemiczne gleby; n.a. – efekty niebadane z uwagi na niespełnione założenia analizy wariancji; pozostałe zmienne (transformowane) analizowano dwuczynnikową analizą wariancji z powtarzanymi pomiarami (czynnik Pg); istotność statystyczna: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

nearly 80% of the total variation in the data (Table 4). The first factor, accounting for 28% of the variation, has strong loading by the total content of the three main heavy metals (Cd, Pb, Zn) and other elements associated with ores (Fe, S) and gangue minerals (K, Ca, Mg, C). This factor is thus interpreted as reflecting the presence/content of mining waste in the soil; pH is also positively correlated with this factor. Factor 2, accounting for an additional 19% of the variation, has strong loading of soil nutrients (total and organic C, N) as well as exchangeable K, Ca and Mg. This factor therefore represents content of nutrients (soil fertility). Factor 3 (explaining 13% of variation) characterises soil texture and is associated with P content (total and available). The last two factors, 4 (11% of variation) and 5 (9% of variation), reflect the variation in the amount of water-soluble and exchangeable pools of heavy metals.

The factors obtained in the factor analysis are completely independent of each other (there is no correlation between them). These factors were therefore used in multiple regression (instead of the original variables) to determine the relationships between the explanatory physicochemical properties of the soil and its biological response parameters. In this analysis, plant species composition is represented by the first two axes of the DCA, as shown by the DCA diagram in Figure 1. Results from the multiple regression analysis are given in Table 5. Factor 1 (representing the presence/content of mining waste in the soil) strongly governs plant species richness and composition. This positive loading contradicts the general consensus that biodiversity decreases with increasing level of anthropogenic pollution. The lack of an expected negative relationship between this factor and plant species richness rather reflects that the total concentration of heavy metals is a poor indicator of environmental toxicity (Smolders *et al.* 2009); instead, the increased availability of other elements associated with the elevated levels of heavy metals (Ca, Mg, K, C and S) is probably of greater importance for plants. There indeed are adverse effects of Cd, Pb and Zn on the ecosystem, but they appear only under soil conditions which render the heavy metals in a water-soluble or exchangeable form. This is substantiated by the negative relationship between factor 5, with a strong loading of exchangeable heavy metal pools, and the abundance of enchytraeids and tardigrades, as well

Table 4. Results of factor analysis of the 25 variables describing the physicochemical properties of topsoil

Tabela 4. Wyniki analizy czynnikowej przeprowadzonej dla 25 zmiennych – właściwości fizycznych i chemicznych górnej warstwy gleby

Factor Czynnik	Explained variance Wariancja wyjaśniona (%)	Variables with high (> 0.5) factor loadings (in parentheses) Zmienne z wysokimi (> 0.5) ładunkami czynnikowymi (w nawiasach)
1	27.8	Zn_T (0.859), Fe_T (0.840), Cd_T (0.834), Ca_T (0.808), Mg_T (0.805), pH (0.791), Pb_T (0.778), K_T (0.664), C_T (0.607), S_T (0.592)
2	18.9	Mg_{EX} (0.855), Ca_{EX} (0.816), K_{EX} (0.804), N_T (0.682), C_{ORG} (0.663), C_T (0.531)
3	13.0	Sand / Piasek (–0.812), Silt / Pył (0.796), P_{OLS} (0.747), Clay / Ił (0.556), P_T (0.536)
4	11.0	Pb_W (0.755), Cd_W (0.662), Zn_W (0.641), C_{ORG} (0.588)
5	8.7	Zn_{EX} (0.735), Cd_{EX} (0.621)

Table 5. Effect of physicochemical properties of topsoil (represented by factors given in Table 4) on the parameters of plant and soil mesofauna communities

Tabela 5. Wpływ właściwości fizycznych i chemicznych górnej warstwy gleby (reprezentowanych przez czynniki; patrz: Tabela 4) na parametry zespołów organizmów glebowych i zbiorowisk roślinnych

Variable Zmienna	R^2	Factor 1 Czynnik 1	Factor 2 Czynnik 2	Factor 3 Czynnik 3	Factor 4 Czynnik 4	Factor 5 Czynnik 5
Number of enchytraeids Liczba wazonkowców	0.187*	−0.075	0.166	−0.013	−0.036	−0.488***
Number of nematodes Liczba nicieni	0.224**	0.204	0.411**	0.305*	0.044	−0.003
Number of tardigrades Liczba niesporczaków	0.059	0.211	0.134	0.052	−0.064	−0.296*
Plant species richness Bogactwo gatunkowe roślin	0.385***	0.388**	0.269*	0.169	0.066	−0.439***
DCA 1	0.393***	−0.365**	−0.341**	−0.407***	0.139	0.149
DCA 2	0.230**	−0.434**	−0.326*	−0.048	−0.021	0.116

Variables explained in Table 1 and in text; R^2 – corrected coefficient of determination; statistical significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Nazwy zmiennych objaśniono w Tabeli 1 i w tekście; R^2 – poprawiony współczynnik determinacji; istotność statystyczna: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

as the number of plant species. This finding is in accordance with extensive literature on the effects of heavy metals on living organisms (e.g. Bååth 1989; Didden and Römbke 2001; Dazy *et al.* 2009). The lack of response of nematodes to soil contamination also has its explanation. Nematodes are a group of invertebrates with different ecological strategies and functions in the food web. The group also has a large range of sensitivity to stress factors, including environmental pollution (Georgieva *et al.* 2002; Pen-Mouratov *et al.* 2008). The high content of heavy metals in the soil, likely to almost eliminate some sensitive nematode species, can thus promote other more tolerant species (e.g. by reducing competition). This results in an overall nonsignificant relationship between the quantitative parameters of the nematode community and the level of contamination.

The effect of the soil environment on the community structure of soil organisms and plants is made clear by a comparison of the polluted Olkusz region with similar unpolluted habitats. For example, the density of enchytraeids, considered a good indicator of soil quality (Römbke and Didden 2001), ranges from 10,000 to 60,000 individuals per square metre in coniferous forests in Poland (Kapusta *et al.* 2003). The values obtained from the slightly polluted forest sites (FS) around Olkusz were approximately an order of magnitude lower. This result is reliable, as it is consistent with findings from other studies (Tosza *et al.* 2010), indicating significant degradation of soils in the Olkusz region.

Conclusions

• The studied soils in the Olkusz mining region cover a large range of physicochemical properties, which differ significantly within and between different land use categories and habitats. This variability is attributable mainly to strong anthropogenic impacts, with large

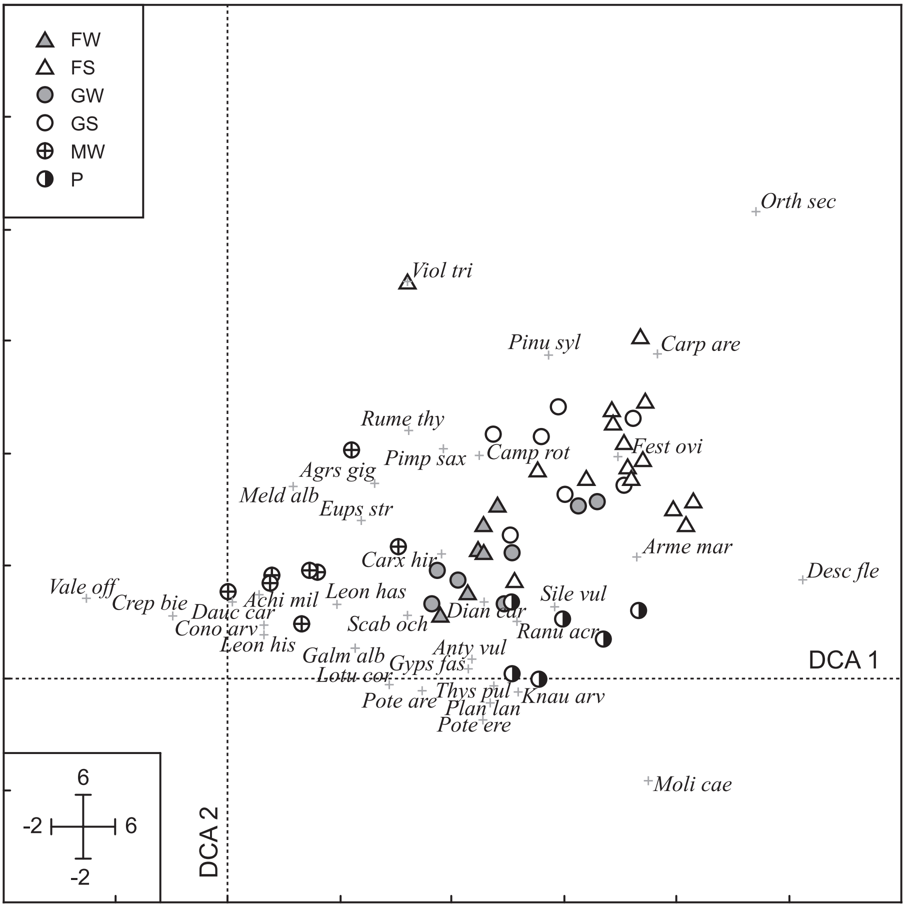

Figure 1. DCA diagram – ordination of the 49 study sites according to plant species composition. First and second axes of DCA explain 16.8% and 7.9% of the variation of species composition of plant communities. Axes reflect the environmental gradients that probably determine the occurrence of plant species: trophic conditions (DCA 1) and humidity (DCA 2). The following species were used in the analysis: *Achillea millefolium* (*Achi mil*), *Agrostis gigantea* (*Agrs gig*), *Anthyllis vulneraria* (*Anty vul*), *Armeria maritima* (*Arme mar*), *Campanula rotundifolia* (*Camp rot*), *Cardaminopsis arenosa* (*Carp are*), *Carex hirta* (*Carx hir*), *Convolvulus arvensis* (*Cono arv*), *Crepis biennis* (*Crep bie*), *Daucus carota* (*Dauc car*), *Deschampsia flexuosa* (*Desc fle*), *Dianthus carthusianorum* (*Dian car*), *Euphrasia stricta* (*Eups str*), *Festuca ovina* (*Fest ovi*), *Galium album* (*Galm alb*), *Gypsophila fastigiata* (*Gyps fas*), *Knautia arvensis* (*Knau arv*), *Leontodon hispidus* subsp. *hastilis* (*Leon has*), *Leontodon hispidus* subsp. *hispidus* (*Leon his*), *Lotus corniculatus* (*Lotu cor*), *Melandrium album* (*Meld alb*), *Molinia caerulea* (*Moli cae*), *Orthilia secunda* (*Orth sec*), *Pimpinella saxifraga* (*Pimp sax*), *Pinus sylvestris* (*Pinu syl*), *Plantago lanceolata* (*Plan lan*), *Potentilla arenaria* (*Pote are*), *Potentilla erecta* (*Pote ere*), *Ranunculus acris* (*Ranu acr*), *Rumex thyrsiflorus* (*Rume thy*), *Scabiosa ochroleuca* (*Scab och*), *Silene vulgaris* (*Sile vul*), *Thymus pulegioides* (*Thys pul*), *Valeriana officinalis* (*Vale off*) and *Viola tricolor* (*Viol tri*). For abbreviations of the habitat types see p. 270, 271

Ryc. 1. Diagram DCA – porządkowanie 49 powierzchni badawczych ze względu na skład gatunkowy roślin. Pierwsza i druga oś DCA wyjaśniają odpowiednio 16,8% i 7,9% zmienności składu gatunkowego zbiorowisk roślinnych. Osie odzwierciedlają hipotetyczne gradienty ekologiczne decydujące o występowaniu gatunków roślin, prawdopodobnie: warunki troficzne (DCA 1) i wilgotność (DCA 2). W analizie brały udział następujące gatunki: *Achillea millefolium* (*Achi mil*), *Agrostis gigantea* (*Agrs gig*), *Anthyllis vulneraria* (*Anty vul*), *Armeria maritima* (*Arme mar*), *Campanula rotundifolia* (*Camp rot*), *Cardaminopsis arenosa* (*Carp are*), *Carex hirta* (*Carx hir*), *Convolvulus arvensis* (*Cono arv*), differences in mineral composition due to the relatively random distribution of deposits of gangue waste from ore mining and slag from metal refineries, as well as the decrease of atmospheric deposition of contaminated dust with the distance from their sources. In addition there are large differences in the degree of soil development.

• Soils in the Olkusz mining area are extremely contaminated with heavy metals. The highest content of Cd, Pb and Zn was found in soils developed directly on waste material from mining, and the least contaminated soils are acid sandy soils under forest.

• Besides the mining waste deposited in the region, important sources of heavy metals are flue emissions from smelters, as well as contaminated dust from wind erosion of tailings ponds and mining waste heaps.

• Although the soils developed on mining waste material are most polluted, they offer much better habitat conditions for plants and soil fauna than the least polluted acid sandy soils under forest. This is due to the high bioavailability of some elements (e.g. K, Ca, Mg, C) associated with heavy metal contamination as well as the limited bioavailability of the heavy metals in the most contaminated soils.

• The activity of soil mesofauna (abundance of enchytraeids and tardigrades) and plant species richness are governed mainly by the bioavailability of heavy metals rather than by total heavy metal content.

• The density of enchytraeids, considered a good indicator of soil quality, is an order of magnitude lower in the Olkusz region than in unpolluted regions of Poland.

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