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ORIGINAL PAPER

Ecological risk assessment based on the TRIAD approach in an area contaminated by the metallurgical and mining industries*

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Abstract

Decisions about how to remediate chemically degraded areas, including those contaminated with heavy metals, should take into account not only the restoration of soil quality but also other factors, such as an ecological risk. The aim of this work was to assess the ecological risk in an area historically contaminated with heavy metals originating from the metallurgical industry and pollution transported from outside the study area, using a multi-stage TRIAD procedure (considering different lines of evidence). This paper presents the results of chemical, ecotoxicological and ecological tests carried out on soils in the Sławków area in the Upper Silesian Industrial Region, one of the most severely polluted regions in Europe, especially contaminated with heavy metals. Conventional risk assessment methods based on determining the level of pollutants in the soil showed high content of heavy metals, especially of Cd, Pb and Zn. This level of pollution requires limiting land use and taking remedial actions. The inclusion of research based on biological methods has significantly expanded the possibilities of an assessment of the actual state of the environment. An environmental risk assessment based on the TRIAD procedure showed that the contamination has potentially fewer negative impacts on the environment and human health than demonstrated by a conventional assessment based on absolute limit values for metals.

Keywords: ecological risk assessment, TRIAD procedure, contaminated soil, heavy metals, phytotoxicity tests

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INTRODUCTION

Environmental pollution with heavy metals is a serious global issue, which is associated with rapid industrialization and urbanization. Soil is a key component of the environment, and sustainable land management is vital for maintaining soil quality (Nriagu, Pacyna 1998). Heavy metal contamination in soil may pose severe health risk to humans and other living organisms in the affected ecosystem (Newman 2014). During the last few decades, people have dramatically altered the biogeochemical cycles of various chemicals. The increasing human population requires larger amounts of energy, other industrial goods, and food, which entails increased emissions of various pollutants, including heavy metals. With the development of economy and society, heavy metal environmental contamination has become increasingly commonplace worldwide. It poses a serious threat in almost every country (Pacyna et al. 2016). It is estimated that the contribution of metals from anthropogenic sources is higher than from natural sources (Vareda et al. 2019).

Heavy metal pollution constitutes a particularly serious problem in soils that are subject to the impact of ongoing and former metal ore mining and processing, and in soils that are in the vicinity of smelting and metallurgical plants, residential and industrial waste landfills, and urban and post-industrial areas (Dmuchowski, Bytnerowicz 2009, Duan, Tan 2013, Dmuchowski et al. 2018, Shi et al. 2023). Combustion of fossil fuels, especially coal, the production of nonferrous metals, iron, steel, and cement, waste disposal, the automotive sector and the production of building materials are the main sources of heavy metal emissions to the air. These emissions are eventually deposited as dry or wet deposits on the soil surface (Martín et al. 2015).

In addition, soils may be directly contaminated due to the application of fertilizers, lime, pesticides, sewage sludge, composts, or discharge of residential and industrial waste, and animal excreta. Heavy metals in fertilizers are mainly derived from ingredients used for their production and from the manufacturing process itself. The content of heavy metals in fertilizers in decreasing order is generally as follows: phosphoric fertilizers> compound fertilizers> potash fertilizers> nitrogen fertilizers (Salazar et al. 2012). Regulations such as the ban on leaded petrol have reduced emissions from motor vehicles; however, this effect has been negated by the increasing worldwide traffic (Monks et al. 2009).

Soil properties may significantly affect heavy metal mobility. The soil capacity for metal binding and conversion from readily soluble (hence more mobile) forms into poorly soluble compounds (bound) ones depends largely on soil pH, granulometric composition and humus content (Antonkiewicz, Gworek 2023). Generally, the metal sorption capacity of soils increases with increasing soil pH and a higher clay and organic matter content. The sorption-desorption processes of trace elements at soil sorption sites are controlled by many factors, such as pH, sorbent characteristics, redox reactions, and the presence of organic and inorganic ligands. At acidic pH, the mobility of toxic elements increases, thereby facilitating their excessive uptake by plants, although some heavy metals are indispensable for plant growth. Elevated amounts of heavy metals may enter the food chain and thus pose a hazard to human and animal health (Weissmannová, Pavlovský 2017).

Heavy metal pollution has drastic effects on macrofaunal communities, the density of which sharply decreases at the highest concentrations of heavy metals (Migliorini et al. 2004). Heavy metals also decrease soil microbiological activity, thus impeding the microbiological decomposition of organic matter (Abdu et al. 2017, Tang et al. 2019). The transfer of trace elements within the soil-plant chain is part of the biochemical cycling of chemical elements and is an element flow from the non-living to the living compartments of the biosphere. Several factors control mobility and availability of elements; in general, these factors are of a geochemical, climatic, biological, and anthropogenic origin. Criteria for environmental protection related to the trace element status in soils should consider all the major variables that govern the behaviour of elements, particularly those that control their mobility and soil-plant transfer ability (Galal, Shehata 2015).

Determination of the heavy metal content of soil is by no means sufficient for a risk assessment. Making an assumption that the total amount of heavy metals in the soil is mobile and available for organisms could lead to discrepancies between the real and estimated mobility of contaminants. In fact, heavy metals can be very mobile in slightly contaminated soil and relatively less mobile in highly contaminated soil. To prevent misinterpretation, risk assessment of contaminated soils should consider bioavailable concentrations, which may be modulated by the physicochemical properties of soils, like pH, clay content, and organic matter content (Grobelak, Napora 2015). Marieta et al. (2017) defined the environmental risk from trace metals in a former mining district in the Vosges Mountains (France) based on the assessment of two biological indicators: (i) the excess of transfer from the soil to biota and (ii) the toxicological risk associated with these excess transfers. An effective evaluation of The Ecological Risk Assessment (ERA) by heavy metals helps determining: (i) bio-accessibility, (ii) bioavailability, (ii) bioaccumulation (Rahman et al. 2017, Yu et al. 2019).

Phytotoxicity tests have increasingly been used as an environmental method to assess the quality of environmental compartments, including soils. The effect of a given soil contaminant on plants depends on many factors, such as its concentration and properties, exposure time, the plant species and soil properties (Wong et al. 2001). Germination and inhibition of growth and biomass production are among the parameters that have been tested most frequently when assessing the soil phytotoxicity of sediments and organic wastes (Adam, Duncan 2001).

Ecological research is a very important contributor to any assessment of the impact of metallurgical industry pollution on the environment. Studies on springtails are used in soil ecotoxicology. They are a good tool for assessing hardly measurable parameters that change over time, and are a source of additional information to help assess environmental effects and trends (Greenslade 2007, Fiera 2009). Springtails are an extremely valuable indicator due to their high sensitivity to changes in the soil chemical properties, such as soil acidification and the content of heavy metals and other toxic compounds (Altieri 1999).

Previous studies have shown that the abundance and taxonomic composition of soil bacteria (including actinomycetes) as well as fungi correlate with the soil nutrient status (Zhou, Ding 2007). Microorganisms are efficient bioindicators because they are ubiquitous in the environment, and due to their short generation time and larger surface area compared to the volume of their cells, they react quickly to physical and chemical changes in the soil (Kennedy, Smith 1995). The ratio of the number of oligotrophic to copiotrophic bacteria (O:C), one of the indices of microbiological changes in the soil organic matter, may be used as a good indicator of the soil biological equilibrium (Bestida et al. 2015).

The ERA, based on the TRIAD approach, implies the integration and then interpretation of the existing information, in order to make a scientific evidence-based risk assessment (Gutiérrez et al. 2015, Niemeyer et al. 2017, Kim et al. 2022). In recent years, the TRIAD methodology has been used to assess the environmental risk of contaminated soils based on a transparent three-line approach evidence (Gutiérrez et al. 2015, Mleiki et al. 2020):

(i) chemistry – chemical: degree of consideration of soil factors controlling contaminant bioavailability, degree of consideration of contaminant properties controlling contaminant bioavailability, route of exposure, repeatability, existence of standardized protocol;

(ii) ecotoxicology – biomarkers, need of modification of the soil sample for the test, degree of relationship between the test species and soil organisms, ecological relevance of the test species;

(iii) ecology – ecosystem health disturbance index, requirement of a control soil (a similar non-contaminated soil) for interpretation, ecological relevance, test sensitivity for ecosystem effects.

Terrestrial isopods (van Gestel et al. 2018, De Smedt et al. 2022), especially the garden snail (*Cantareus apertus*), are used as indicator organisms for the soil environment (Mariet et al. 2017, Mleiki et al. 2020). Some recent soil quality indicators developed using land snails are help to highlight potential transfer of metals to living organisms, including humans (Mariet et al. 2017).

The aim of the study was to assess the ecological risk in an area historically contaminated with heavy metals from the metallurgical industry, local emissions from transport and low emissions, as well as pollutants transported from outside the studied area. The assessment was carried out using the multi-stage TRIAD procedure and taking into account various lines of evidence.

STUDY AREA

The research area was located in the town of Sławków (geographical coordinates: 50°17′57,9480″N 19°23′22,8120″E) and adjacent areas, in the eastern part of southern Poland, more specifically in the Upper Silesian Industrial Region (Figure 1). The area remains within the impact range

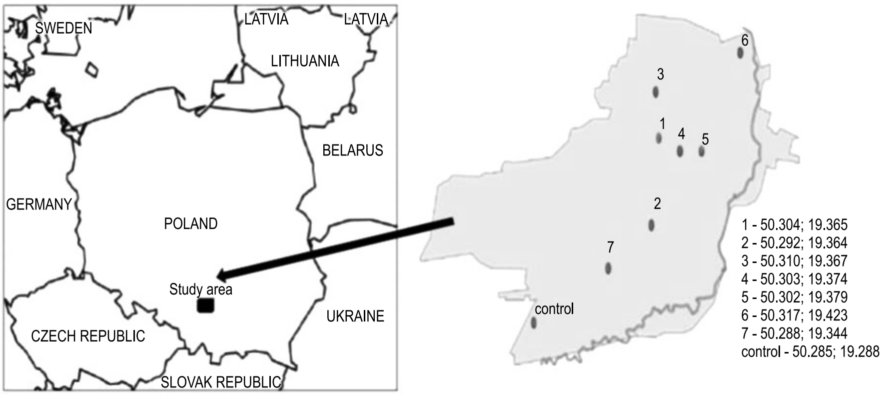

Fig. 1. Location of study area

of Poland's main industrial centre and of transboundary emissions from the south, transported through the Moravian Gate from Moravia, the Czech Republic. The region is one of the oldest European centres of metallurgical industry. The Upper Silesian Industrial Region includes many industrial facilities that emit high levels of pollution, including heavy metals. The whole region has been identified as one of the most polluted areas in Europe, and is often referred to as an environmental disaster area. In the Sławków region, intensive industrial production, mainly associated with the processing of various metals, has been going on since the Middle Ages. Currently, the Sławków region is influenced by the import of pollutants from nearby emission sources as well as long-distance transport. The closest large source of heavy metal emissions is a zinc and lead smelter at Bukowno near Olkusz, lying at a distance of 14 km (Dmuchowski et al. 2011, Azarbad et al. 2013).

Heavy metal emissions that are particularly disruptive for air quality generated by industrial works in the Upper Silesian Industrial Region accounted for 85.9% of Cd, 78.7% of Pb, 62.9% of Zn, 30.5% of As and 24.8% of Hg emitted in Poland, though the region constitutes only 4% of the area of the country (Environment 2017).

Seven representative test sites were established in the area heavily affected by the historical direct impact of the lead, zinc, and ore industry. Sites 4 and 5 were in zones used since the first century AD as primitive metallurgical furnaces (bloomery furnaces) for smelting metals. A wasteland with degraded soil covered with grass vegetation was also selected. One reference (control) site was a relatively less contaminated area located outside direct historical and current emission sources. The contamination at this site can be considered as the background level for the Upper Silesian Industrial Region (Figure 1).

MATERIALS AND METHODS

Chemical analysis of soil

The procedure for the preparation of soil samples and chemical analyses was performed in accordance with the methodology provided by Allen et al. (1974). The material for analysis was collected from the topsoil (0-20 cm). Eight samples (approx. 1 kg) from which a composite sample was made were collected from each of the seven locations and control. All laboratory analyses were performed on composite samples.

The following parameters were determined in soil samples collected from topsoil horizons: the sand fraction was determined by the sieve method, while the finer fraction was determined by the Casagrande's hydrometer method in the modification of Prószyński. The soil material was also analysed for basic chemical properties, including organic carbon content, using a TOC – 5000A apparatus with an SSM-5000A adapter made by SHIMADZU; pH was determined in H_2O and KCl using the potentiometric method; the nitrogen content was determined with the Kjeldahl method; hydrolytic acidity was determined with the Kappen method; exchangeable cations were determined by atomic absorption spectrometry (AAS) after extraction with 1 molar ammonium acetate solution using a Varian Vista Pro apparatus.

Heavy metals in the soils, including Zn, Cd, Cr, Cu, Ni and Pb, were extracted with aqua regia (mixture of hydrochloric acid and nitric acid, in a molar ratio of 3:1) in a mineralizer (Berghof SpeedWaveFour). The analyzed elements were determined in the extractant by atomic emission spectrometry with plasma excitation using a Varian model Vista PRO.

Quality control (QC) for the metal content in the plant samples was performed using certified reference materials for light sandy soil from Metranal (LSS-31, the Czech Republic) (Table 1). The results were in good agreement with the certified values. The recovery range was from 93.1 to 101.4%.

Table 1

Comparisons of measured and certified concentrations of metals (mg kg^{-1}) in certified reference material (Light Sandy Soil LSS-31, from Metranal, Czech Republic)

	Zn	Cd	Cr	Cu	Ni	Pb
Certified	43.3± 2.2	0.29± 0.07	71.9± 5.9	28.9± 0.9	31.8± 1.2	24.1± 1.7
Measured	43.0±3.5	0.27±0.02	71.6±5.7	29.3±2,4	30.6±1,8	23.4±1.5
Recovery (%)	99.3	93.1	99.5	101.4	96.2	97.1

Phytotoxicity analysis

To determine the phytotoxicity of the investigated soil samples, a Phytotoxkit test set (MicroBioTests Inc., Belgium) was used to assess early plant growth. The test used three species of dicotyledonous and monocotyledonous plants: cress (*Lepidium sativum*), mustard (*Sinapis alba*) and sorghum (*Sorghum saccharatum*). The tests were carried out on soils sampled from the investigated area and the standard OECD (2010) soil for each of the plant species listed.

The soil samples were sieved through a 1-mm sieve and soaked with distilled water to 100% WHC (water holding capacity), placed on special test plates and covered with blotting paper. Ten seeds of the respective plant species were placed on each test plate and incubated in the dark for 72 h at 25°C. After the incubation period, the number of germinated plants was counted, and photographs of the plates were taken. The length of roots was determined using digital image analysis with ImageJ open-source software (National Institutes of Health, USA). The percent inhibition was calculated as follows:

$$I(\%) = \frac{\text{Average root length in the soil (OECD)} - \text{Average root length in a sample}}{\text{Average root length in a sample}} * 100$$

Ecological analyses

Number and species structure of springtails (Collembola)

Hexapods and springtails were used for ecological analyses. In the laboratory, springtails were extracted from soil samples from two depths: 0-5 cm and 5-10 cm in a high-gradient Macfadyen extractor (Macfadyen 1961). The samples were exposed to the temperature gradient for 120 h and then preserved in 70% ethylene alcohol. The taxonomic analysis of the springtails was carried out using basic manuals (Fjellberg 2007). The number of springtails was counted for the three morphology-based life forms according to Gisin's classification (Gisin 1943): epigeic, hemiedaphic and euedaphic species, which inhabit the herbaceous and litter cover of the soil surface, the litter and topsoil, and the deeper soil layer, respectively. Moreover, the springtails were divided according to their dispersal abilities into high-mobility and low-mobility species. Epigeic species were considered highly mobile, and hemiedafic and euedaphic species were considered as not very mobile.

Number of bacterial trophic groups

In the laboratory, fresh soil samples were used to prepare 10 g test portions, which were used to make soil suspensions of varying concentrations in sterile tap water. Subsequent dilutions were made from the primary suspensions. In the soil samples, the number of oligotrophic and copiotrophic bacteria was determined by a plate method according to the Koch procedure on an adequate solid agar medium with antifungal antibiotics (actidione, 50 μg ml^{-1}). The number of bacteria was converted per soil dry matter and expressed as colony forming units (cfu g^{-1} d.m. soil) (Hattori, Hattori 1980). The number of oligotrophic bacteria was counted on 1000-fold diluted nutritive broth (BTL) at 28°C after 21 incubation days. The number of copiotrophic bacteria (cfu g^{-1} d.m. soil) was determined on nutritive broth (BTL) at 28°C after seven days of incubation.

Spatial ecological risk assessment

To carry out a field risk assessment according to the TRIAD method, the concentration of metals in the soil was determined, and an ecological assessment of selected soil samples (one reference soil) and other samples with different levels of contamination was carried out (Ribé et al. 2012).

Environmental risk analysis based on the TRIAD multi-stage procedure using t The Standard Advanced Dewar Assembly (SADA) program reveals the extent of threats to human health and to the soil environment in the area under study. A spatial assessment of ecological risk was performed using the Spatial Analysis and Decision Assistance software, a program designed to assess threats due to various factors (Stewart et al. 2009). This program enables the development of two- and three-dimensional maps of pollution distribution in the area under study as well as performing statistical analyses, developing decontamination scenarios and determining the level of risk for humans and the environment. It is an application focused on spatial research and the design of soil remediation strategies. The application of the SADA program allows (Stewart, Purucker 2011, Gworek et al. 2018):

(i) the integration of data on the size and location of pollution;
(ii) the provision of information on the size of the risk, and if necessary, the addition of pollution information for contaminants, including unregulated contaminants;
(iii) support for the management of degraded areas.

The results obtained in this study were statistically analysed using Statistica 13 software. A comparison of means was performed using one-way analysis of variance, and multiple comparisons of means were performed based on the Tukey's HSD procedure. The significance level of 0.05 was assumed for the analyses (Sokal, Rohlf 1995).

RESULTS AND DISCUSSION

Results of chemical analyses

Physicochemical characteristics of soils

An essential step of the research was to determine the physicochemical properties of the soil. Table 2 shows the granulometric composition of the soil from all research areas. Considering their granulometric composition,

Table 2

Granulometric composition of analyzed soil samples

Site No	Percentage share of fraction, size of fraction (mm)			
	gravel	sand	silt	clay
	(>0.20)	(2.0-0.05)	(0.05-0.002)	(<0.002)
1	1.4	64.8	16.0	11.0
2	1.3	71.0	14.0	10.0
3	0.9	65.4	17.0	15,0
4	2.7	39.6	23.0	29.0
5	1.6	50.0	18.0	28.0
6	0.1	9.0	60.0	27.0
7	2.5	40.8	20.,0	33.0
Control	3.4	67.2	13.0	10.0

the soils were classified as clay soils. The top layers of soils sampled from sites 1 and 3 were described as light clays, those from site No. 2 and the control as sandy loams, those from sites 4 and 5 as clay loams, and those from site no. 6 as silty loams. The content of the clay fraction significantly influences the total amount of heavy metals in soils. However, minerals can be contained in this fraction due to their sorption properties. These soils decrease the mobility and bioavailability of trace elements, which offsets their translocation in the soil profile (Terelak et al. 1997).

The basic chemical properties of the soils are given in Table 3. The soils exhibited a range of pH values from acidic to neutral. Distinctly higher pH values were found in soils from study sites 1, 3, 4 and 5 than in the remaining sites. The largest amount of nutrients, like K, Ca and Mg, was found in soils at sites 4 and 5, which apparently resulted from the high level of total carbon and the presence of carbonates in these soils. Aluminium cations were found in soils with pH values below 5.84. The soils were characterized by low nitrogen content (N).

The content of heavy metals in soils

The content of heavy metals (Cr, Cd, Ni, Pb, and Zn) in the soil varied significantly depending on the location. The highest levels of these elements were found in soils sampled from sites 4 and 5, while the lowest levels were found in soils from the reference site (Figure 2.). As mentioned earlier, hundreds of years ago, simple, single-use metallurgical furnaces were located in the area of research sites 4 and 5. It can be inferred that we are dealing with historical soil contamination with Zn and Pb in this area.

Table 4 shows the content of metals in soil from highly polluted industrial areas and the background levels according to various authors.

The contents of Cr, Cu and Ni in the soil in the samples from the control

Table 3

Basic chemical properties of investigated soils (0-20 cm)

Site No	C total	N	$CaCO_3$	pH H_2O	pH KCl	H_h	Al+H_w	H_w	Al	Na	K	Ca	Mg
		Milliequivalent 100 g^{-1} of soil				Cations mg 100 g^{-1} of soil							
1	3.060	0.252	0.0	6.98	6.52	0.956	0.000	0.000	0.00	1.9	2.0	727.5	52.5
2	4.554	0.426	0.0	5.37	4.66	5.576	0.569	0.223	0.34	1.5	2.1	207.3	63.4
3	2.125	0.214	0.0	7.15	6.82	0.615	0.000	0.000	0.00	2.0	4.3	440.0	115.0
4	5.605	0.367	20.6	7.31	6.60	0.713	0.000	0.000	0.00	1.9	4.8	1817.5	80.0
5	2.888	0.293	5.1	7.15	6.43	0.859	0.000	0.000	0.00	1.5	7.3	917.5	80.0
6	1.720	0.212	0.0	5.84	5.20	2.370	0.368	0.158	0.21	2.3	3.9	189.8	67.3
7	3.480	0.295	0.0	4.52	3.89	6.053	1.219	0.315	0.90	1.8	3.1	171.6	39.6
Control	6.635	0.477	0.0	5.02	6.71	7.973	1.199	0.757	0.44	2.3	1.6	235.9	28.5
OECD	3.45[1]-4.11[2]	0.04[1]		5.96[3]	5.5-6.5[1]								

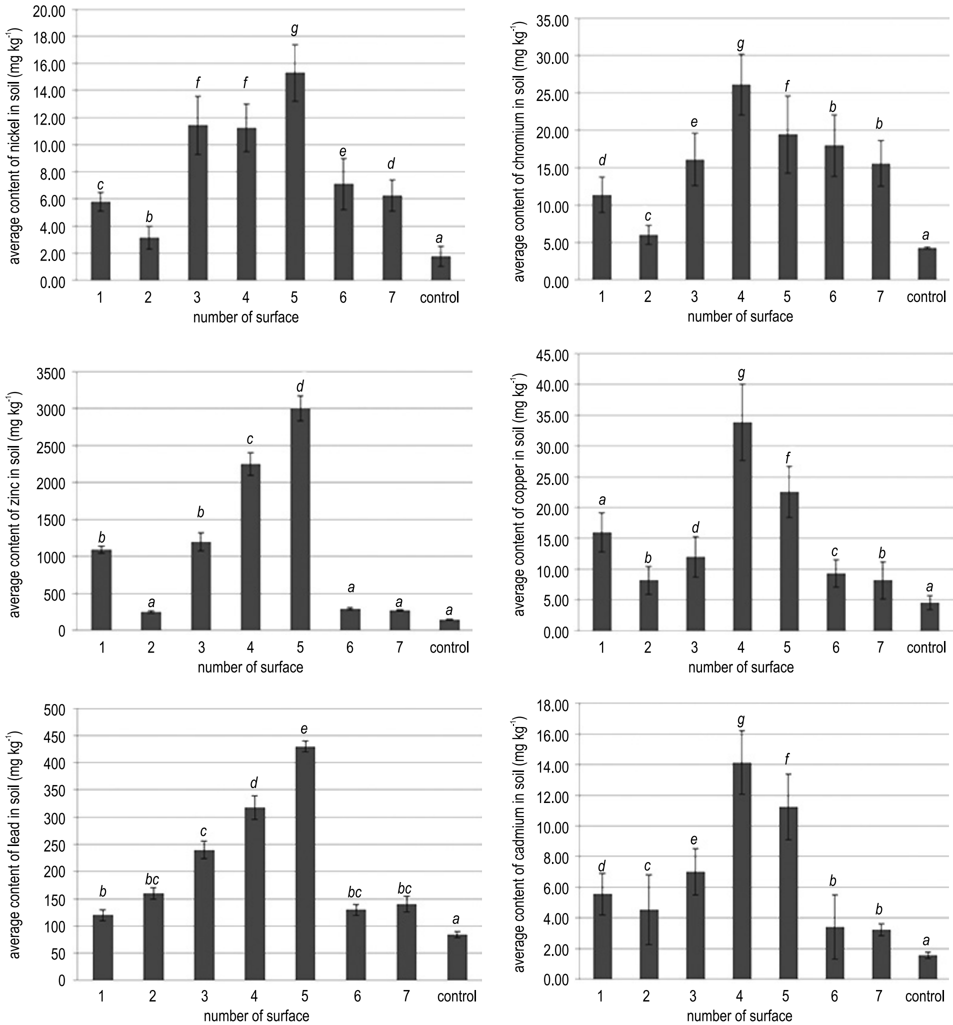

Fig. 2. Average content of heavy metals in soils from the designated study sites (mg kg-1)

and study areas were comparable to the background level for Poland and China, which indicates the absence of contamination with these metals (Figure 2). However, the contents of Cd, Pb and Zn in the control sample were much higher than the background values for Poland and China, by 159-195%, 324-337%, and 571%, respectively (Qing et al. 2015).

The contents of Cr, Cu, and Ni in the soil from the city of Sławków were higher than those in the control samples (Figure 2). The highest values were measured at sites 4 and 5, but the Cr, Cu, and Ni contents in all samples were close to the levels defined as the background levels for Poland and China. The contents of Cd, Pb, and Zn in the soil were much higher. The highest values were measured in sample No. 5 (Zn, 3000 mg kg^{-1} and

Table 4

Some examples of surface soil layer contamination with metals in regions of important sources of emissions and in background pollution areas by various authors

Localization	Source of pollution	Metal content in the soil (mg kg^{-1})					Authors
		Cd	Cr	Cu	Pb	Zn	
Total background							
Poland		0.22-0.86	7-20	5-23	14-25	32-91	Kabata-Pendias (2010)
China		0,10	61	23	26	74	Qing et al. (2015)
Pollution areas							
Olkusz, 14 km from Sławków, Poland	Pb/Zn smelter	77	-	42	2 949	4 249	Azarbad et al. (2015)
Bukowno S Poland	landfill mining/metallurgy	20.1	-	-	1641	802	Pietrzykowski et al. (2018)
Upper Silesia (Poland)	main industrial region (max.)	143	-	-	8 200	12 592	Helios-Rybicka (1994)
Poland	Cu smelter	-	-	-	2 000	7 000	
Czech Republic	Pb/Ag smelter	68	-	-	4 705	3 395	Ettler et al. (2005)
	Pb smelter	-	-	-	35 300	-	Vaněk et al. (2005)
Turkey	industrial zone	143	725	725	8 469	>10 000	Yaylalı-Abanuz (2011)
China	Pb/Zn smelter	75	183	316	24 859	8 078	Li et al. (2015)

Pb, 430 mg kg^{-1}), higher by 2070% and 510%, respectively, than those in the control sample. The highest content of Cd was found in sample No. 4 (14.1 mg kg^{-1}), which was 881% higher than that in the control sample. These historical pollutants indicate that zinc-lead smelting was carried out in this area. The content of heavy metals in soil, especially those of Cd, Pb, and Zn, was at a very high level, characteristic of areas under the influence of metallurgical industry emissions, especially of emissions from nonferrous metallurgy (Yang et al. 2018, Zhang et al. 2018).

Results of toxicological tests

Table 5 presents the results of the Phytotoxkit test carried out using the three plant species and the three parameters tested, i.e., germination and the inhibition of the shoot and the root growth. It was found that germination was only slightly affected by the location of a soil sampling site and the level of soil metal pollution. In the case of the inhibition of root elongation and shoot growth, the diversity among species, location and pollution was much greater, but the statistical analysis of the results showed no significant relationships.

Despite the large variation in the soil metal content, no significant differences were found in the test plants' responses. This could suggest that these metals occur in chemical forms that did not have a significant negative effect on germination or root and shoot growth in the test plants. After the ore smelting process, slag remained as a waste product containing metal oxides in single-use furnaces (see chapter Study Area). Therefore, it can be concluded that this form of metals is not significantly toxic to the selected test organisms.

Results of ecological research

Number and species structure of springtails (Collembola)

The number of springtails found in the two soil layers is shown in Table 6. As a rule, the springtails were not numerous, and no patterns were found in the number of springtails and the locations, the degree of metal soil contamination, or the sample depth.

The lack of obvious effects of metal contamination means that many factors can influence the response of springtails. In the case of long-term contamination, both a decline (e.g., Hågvar, Abrahamsen 1990) and an increase in collembolan numbers (e.g., Hopkin, 1989) were recorded. It is known that environmental conditions, especially temperature and humidity (e.g., Huhta, Hänninen 2001), environmental preferences and mobility of individuals (e.g., Auclerc et al. 2009), food availability (e.g., Chauvat et al. 2014) and biotic interactions, especially competition, can significantly modify the number of springtails. It is important to note that in contaminated environments, the number of springtails begins to be significantly influenced by competition (Rusek, Marshall 2000). In the present study, the above species occurred

Table 5

Inhibition of germination, shoot growth and root elongation in *Lepidium sativum*, *Sinapis alba* and *Sorghum saccharatum* (% effect) in the investigated soils, in relation to soil according to OECD

Site No	Germination			Shoot inhibition			Root inhibition		
	Lepidium sativum	*Sinapis alba*	*Sorghum saccharatum*	*Lepidium sativum*	*Sinapis alba*	*Sorghum saccharatum*	*Lepidium sativum*	*Sinapis alba*	*Sorghum saccharatum*
1	0.00	5.00	-5.56	8.72	-17.82	-55.85	18.09	19.81	-24.92
2	5.00	0.00	-11.11	31.44	6.42	-102.48	-12.05	-10.03	-49.70
3	0.00	0.00	11.11	8.81	-8.73	-51.73	28.11	41.34	11.50
4	0.00	0.00	0.00	-5.01	-34.78	-63.18	-3.03	22.43	-10.05
5	5.00	0.00	0.00	-2.47	-43.57	-113.08	9.21	19.55	-22.56
6	0.00	0.00	5.56	44.99	18.37	-61.74	41.25	23.47	-16.13
7	5.00	5.00	11.11	42.48	26.22	-46.58	-4.25	-2.32	-13.83
Control	0.00	0.00	11.11	34.31	27.43	-49.11	-19.23	2.17	-47.53

Table 6

Average abundance of springtails – *Collembola* (N 1000 m^{-2} ± SD) in the respective soil layers

Depth (cm)	Site, No							
	1	2	3	4	5	6	7	Control
0-5	1.0±1.0	0.3±0.6	1.3±1.1	0.0±0.0	0.0±0.0	1.3±1.5	6.0±2.0	0.3±0.6
5-10	1.0±1.7	0.0±0.0	0.7±1.1	0.3±0.6	0.3±0.6	0.0±0.0	0.3±0.6	0.0±0.0

in sites characterized by relatively high levels of contamination with heavy metals (site 1 and site 3) – Figure 2.

Another species found at site No. 1 was *Proisotoma minuta*, which is characterized by a short life cycle and relatively high resistance to contamination, especially mercury contamination (Buch et al. 2016) – Table 6. Sensitivity to soil contamination is often associated with different life stages (e.g., Buch et al. 2016). An example is *Sminthurus viridis*. Only some life stages of this species are sensitive to pollution (Bishop et al. 1998), which may explain its presence at a relatively heavily contaminated site (site 3, Table 6). However, the cost of these adaptive mechanisms is high, which means that resistance to heavy metal contamination is usually accompanied by sensitivity to other environmental factors (Tranvik, Eijsackers 1989).

In summary, the number of springtails in contaminated environments depends on many factors, not only the contamination itself but also abiotic and biotic environmental conditions that can modify the impacts of contamination. The effect of long-term contamination is not so much a change in the number of springtails, but in the specific species composition of their communities. These communities were dominated by species with strong dispersion ability showing high tolerance to environmental factors in competition with species that were not adapted or poorly adapted to life in contaminated environments. The species found in the study sites are widespread and occur in various environments.

Number of selected trophic groups of microorganisms

The heterotrophic bacteria were divided into two groups, copiotrophs and oligotrophs, which differ based on the quantity and quality of nutrients needed for their growth and development (Krzyżak et al. 2013). Research findings obtained by Bastida et al. (1966) demonstrate that the ratio of oligotrophic to copiotrophic microorganisms may be used as a good indicator of the soil biological balance, while the quantitative relationship between those microorganisms, referred to as the O:C (oligotrophs to copiotrophs) ratio, can provide an indicator of microbiological changes in the soil organic matter.

The number of bacteria in the soil is shown in Figure 3. The highest number of copiotrophs was found at sites 3, 4 and 5, and the highest number of oligotrophs was found at sites 4 and 5. The highest metal content in soil was also found at these sites. This suggests that, surprisingly, there is an

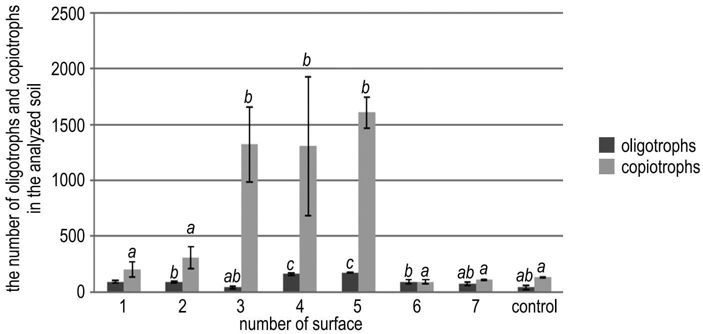

Fig. 3. The number of trophic groups of bacteria in investigated sites

increase in the number of microorganisms with the increase in heavy metal contamination in the soil. There seems to be a controversial phenomenon indicating an increase in the number of microorganisms with an increase in soil heavy metal pollution. The reason for this phenomenon may be the presence of the investigated metals in their oxide forms, with significantly limits availability for soil organisms. Moreover, microorganisms have developed various heavy metal resistance mechanisms that help them survive in an environment containing toxic concentrations of trace elements (Girma 2015).

Interpretation of results using the SADA software

The results of the analysis of the spatial distribution of soil contamination are presented in the form of maps with isolines (Figure 4), where the individual colours are assigned to specific concentrations of the heavy metals. The distribution of isolines on the maps shows that sites 4 and 5 can be considered the most polluted. These sites are located in the nearest proximity of the town of Sławków. The ecological risk analysis performed on the basis of the multi-stage TRIAD procedure, which combines chemical measurements, ecotoxicological tests and observations of selected organisms, and the SADA software revealed the range of threats to human health and to the soil environment in the investigated area.

The spatial risk analysis showed that certain areas are heavily contaminated with heavy metals and are also a source of their secondary release. Areas historically associated with the extraction and processing of metal ores are still considered contaminated due to the increased content of trace elements in soil and water, which pose a real threat to the environment. Currently, there is no smelting and mining activity in the study area (town of Sławków), but this area creates a secondary source of contaminants that are released and deposited in soil and water. The respirable dusts in the air, which are the main carriers of pollution, are particularly dangerous to humans. However, this area is also influenced by industrial emissions from neighbouring areas.

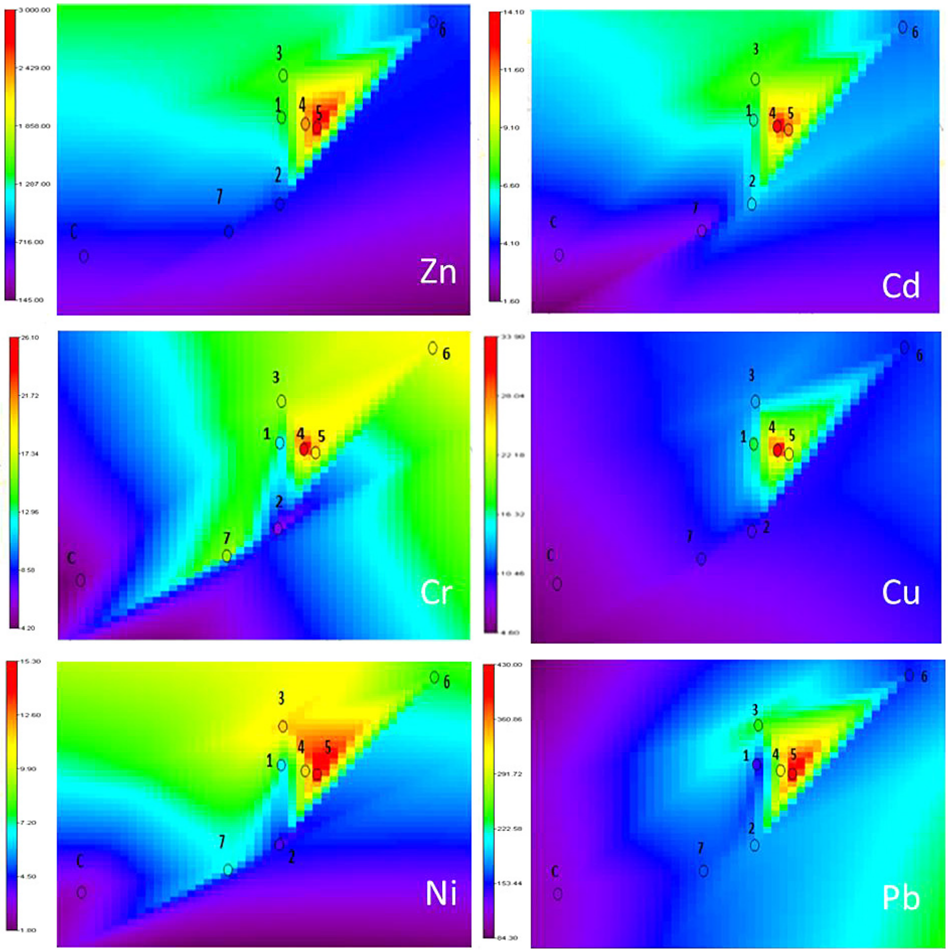

Fig. 4. Maps of heavy metal (Zn, Cd, Cr, Cu, Ni and Pb) contamination

The application of the TRIAD procedure for assessing risks in the region exposed to contamination by heavy metals allowed us to identify areas of high ecological risk, which should be excluded from agricultural use (part of the area is used as allotments) and remediated. This area is mainly in the vicinity of study sites 4 and 5. In view of the level of threat to the soil and the risks involved, it is vital that the area undergo reclamation; however, the choice of a reclamation strategy is not simple and always requires individual analyses of the issues and consideration of local conditions. The elevated levels of zinc, chromium, cadmium and lead result from the historical conditions of this area and its industrial character. The indicated sites should be considered a serious threat to people and the soil environment as well as to basic ecological functions. The spatial risk analysis shows that sites indicating sources of heavy metal release are located where Zn and

Pb ores were smelted hundreds of years ago, so this is primary pollution. In turn, this area is a source of secondary pollution because of the erosion of these soils. This pollution source is especially dangerous for people who inhale the air containing respirable dusts, which are carriers of pollution (Shenoy et al. 2018). The lowest concentrations of metals were recorded at soil sampling site No. 6, the most distant site, located to the northeast of Sławków. Likewise, relatively low concentrations of heavy metals were found in soils sampled from sites 2 and 3 to the southwest of Sławków.

Environmental risk assessment for the studied historically contaminated area, mainly with Zn and Cd, based on the TRIAD approach, which takes into account chemical, ecotoxicological (simple, standardized biotests) and ecological (e.g., microbiological parameters) measurements, allowed obtaining a more precise answer as to the possibility of risk occurrence than an assessment based on traditional cutoff numbers. The latter approach is based on the determination of the total content of a given pollutant / element and does not provide knowledge about its mobility and thus its environmental risk. In the analyzed case, in a chemically degraded area due to the method of smelting metal ores in a primitive way, metal residues in the soil occur in a form that does not constitute an ecotoxicological and ecological risk. They are usually oxide forms, not very mobile and difficult to release into the environment, therefore they cause far fewer negative effects on the environment. Environmental risk assessment based on the TRIAD procedure allows optimizing the management of chemically degraded land as well as selecting an appropriate remediation method. The safe level of soil contamination is not always within the limit numbers and the case presented in this paper is a proof.

CONCLUSION

The town of Sławków, located in Upper Silesia, is one of the most historically polluted European regions, especially with heavy metals. Conventional methods of risk assessment based on determining the levels of contaminants in the soil showed high contents of especially of Cd, Pb and Zn. This level of pollution requires limiting the land use and performing remediation actions. However, our research has shown that chemical methods are insufficient to properly assess the degree of pollution risk. The inclusion of research based on biological methods greatly expands the possibilities of current evaluation. For example, studies on springtails showed that environmental pollution affected their species composition but not their number. Species with strong dispersal abilities and high tolerance to environmental factors dominated.

The multi-stage TRIAD procedure, combining chemical measurements, ecotoxicological studies and observations of selected living organisms, and the SADA software enabled a comprehensive description of the range of threats to human health and the environment in the study area. In the analyzed case, in the area chemically degraded mainly by the metallurgical industry, metals are largely present in low-labile forms (oxides and sulfides), which limits their release to the neighbouring soil environments. As a result, they cause significantly fewer negative effects on the environment and human health than indicated by a conventional assessment based on the determination of limit values for metal content. Environmental risk assessment based on the TRIAD procedure facilitates better optimization of the management of chemically degraded land and the selection of an appropriate remediation method.

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