Journal of Geochemical Exploration 184 (2018) 261–270

Contents lists available at ScienceDirect

Journal of Geochemical Exploration

journal homepage: www.elsevier.com/locate/gexplo

Environmental impact of disposal of coal mining wastes on soils and plants in Rostov Oblast, Russia

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ARTICLE INFO

Keywords:
Soil pollution
Technogenic anomalies
Heavy metals
Geochemical impact assessment

ABSTRACT

Underground coal mining in Southern European Russia leads to soil cover destruction in areas directly occupied by spoil tips and rock dumps located nearby. Coal producing areas in Rostov Oblast were selected for a detailed consideration. Soil samples were taken from the uppermost horizons: a layer of 0–10 cm of spoil tips and surrounding areas, as well as from 1.5 m depth vertical soil profiles. The soil samples were analysed for mineral composition, particle-size distribution and gross contents of Cu, Zn, Pb, Ag, Sn, Mo, Ba, Co, Ni, Mn, Ti, V, Cr, Ga, P, Li, Sr, Y, Yb, Nb, Sc and Zr, using emission spectral analysis. The plant species of mining influenced areas were described. The process of Technosol formation at the waste sites was considered separately. Soils have not yet formed as a result of a self-restoration on the spoil tips aged more than 50 years and burnt-out decades ago. A vegetation cover, which emerged during this time range, practically does not support the progress of any considerable soil-forming process. The ponds formed by the flooding of burning spoil tips, do not give the possibility for the formation of soils and hardly contribute to plant growth. The surface layers of spoil tips at all stages of their development are different from the surrounding steppe soils in geochemical characteristics and mineralogical composition. The atmospheric and water inflow of material from spoil tips changes (in the cases studied - worsens) a state of steppe soils within a radius of 1 km, and leads to the increase of heavy metal content in these soils.

1. Introduction

Soils are amongst the most important natural resources, defining sustainable development and independence of states. In recent decades, the geochemical characteristics of soils have undergone significant changes under the influence of anthropogenic activities worldwide (Gerasimova et al., 2003; Kasimov and Perel'man, 1992).

Land areas disturbed by mining activities in Russia are amounted to > 13,000 km^2 by now. > 10% of disturbed soils are occupied by storage territories of mining wastes, which are produced during mineral resource extraction and processing (Alekseenko et al., 2017; Martínez-Sánchez et al., 2012). Due to the low quality of safety and remediation measures, this leads to a wide range of negative effects (Mezhibor et al., 2011). The latter are pollution of air, soils, sediments and vegetation (Bech et al., 2012), surface and ground water quality deterioration (Balykin et al., 2013; Chalov et al., 2015a; Pashkevich et al., 2015; Puzanov et al., 2015), increase in morbidity and mortality (Rikhanov et al., 2011), reduction of the number of plant and animal species (Bezel et al., 2015; Boyarskikh et al., 2013), and loss of visual aesthetic landscape characteristics (Cehlár et al., 2016).

The largest geochemical changes related to technogenic impact have generally occurred in soils (Vernadsky, 1965). The landscape in mine areas is a medium where high contents of potentially toxic elements are deposited and saved for decades (Timofeev et al., 2016). Mining and processing are customarily considered as one of the key soil contamination sources (Alekseenko and Pashkevich, 2016; Beloglazov et al., 2016; Chalov et al., 2015b; Khoroshavin and Moiseenko, 2014; Mishra et al., 2008; Titov and Beloglazov, 2015; Younger, 2004). Thus, the questions for the case study of coal mining impact were formulated as follows:

1. Could we state that underground coal mining, conducted by modern

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http://dx.doi.org/10.1016/j.gexplo.2017.06.003
Received 18 July 2016; Received in revised form 19 January 2017; Accepted 5 June 2017
Available online 10 June 2017
0375-6742/

Fig. 1. The studied area in Rostov Oblast, Russia (a basemap: http://www.ipa-don.ru).

ways, leads to soil destruction in Rostov Oblast of Russia?
2. Has a soil cover formed following a self-restoration of the burnt-out spoil tips after a half-century period?
3. Do the surface layers of spoil tips differ from the surrounding steppe soils in geochemical and mineralogical patterns?
4. How does the atmospheric and water inflow of material from spoil tips change heavy metal contents in steppe soils?

To consider the basic processes of soil restoration, it was selected a number of areas where coal mining had been performing for several decades and had caused several environmental problems.

2. Material

2.1. Study area

The self-restoration of certain landscapes (Bradshaw, 1997, 2000; Li, 2006; Sklenicka, 2012; Tropek et al., 2012) and soils (Bodlák et al., 2012; Wong, 2003) disturbed by underground coal mining was examined using as example the Donets Coal Basin in Rostov Oblast, Russia (Fig. 1). Coal is not mined in the studied area nowadays, but its extraction still occurs in the Donets Coal Basin in Rostov Oblast.

Each thousand tons of mined coal in that region is accompanied by three hundred tons of waste rocks lifted on the surface. Hence, a large number of spoil tips is deposited over previously existed natural soils (Bragina and Gerasimova, 2014). Both the deep occurrence depth of coal beds and their low thickness (0.6–1.5 m) cause huge amounts of rocks moved to the surface in the course of development and breakage headings.

Over 1500 spoil tips are formed on the territory of the Donets Coal Basin, having a bulk volume of more than a thousand million m^3. The spoil tips occupy an area exceeding 8000 ha where the previously existed soils of steppes and farming lands are irretrievably annihilated. A coal-containing body of rock in spoil tips often heats up following oxidation processes (Bian et al., 2009; Castleden et al., 2011; Zhang et al., 2012) and spontaneously combust liberating toxic gases (Senapaty, 2012). Spoil tips combustion (Photo 1) may continue for decades (Mohapatra and Goswami, 2012), polluting adjacent soils and causing plant failure, which also affects soil patterns (Das and Chakrapani, 2011; Querol et al., 2008; Shi et al., 2013).

Photo 1. A burning spoil tip (arrows indicate the escaping gases).

2.2. Sampling

Geochemical landscape maps (1:500,000 scale) were used as a sampling basis. The maps were compiled and published under the supervision and with the participation of a co-author (Alekseenko et al., 2002). The Main Department of Geodesy and Cartography under the USSR Council of Ministers published a series of geochemical landscape maps edited by A.I. Perel'man as a result. The classification of terrestrial geochemical landscapes (Table 1) was a basis for the maps. According

Table 1
Classification of terrestrial geochemical landscapes (after V.A. Alekseenko).

Classification levels	Landscape characteristics considered at the level	Examples of landscapes of each level								
I	The leading migration pathway	Biogenic			Technogenic					Abiogenic
II	Peculiarities of the leading migration pathway	1. Forests 2. Steppes 3. Deserts 4. Tundras 5. Primitive deserts	Forests: 1. Deciduous 2. Mixed 3. Coniferous	Deciduous forests: 1. Oak-hornbeam 2. Alder 3. Poplar, etc.	1. Planted forests 2. Agricultural 3. Industrial 4. Urban 5. Road 6. Mining 7. Military	Agricultural: 1. With rotation of annual crops 2. Perennial crops 3. Cattle-breeding	Perennial crops: 1. Gardens 2. Vineyards 3. Tea plantations 4. Berry plantations 5. Nut plantations	Annual crops: 1. Amended 2. Not amended	Amended: 1. Dehumidified 2. Irrigated 3. Periodic	Glaciers
III	Soil properties	1. Oxidising environment (available O_2) 2. Reductive gley environment (not available O_2 and without H_2S) 3. Hydrogen sulphide environment (not available O_2 and with H_2S)			1. Ultra acidic (pH < 3) 2. Acidic to moderately acidic (pH 3–6.5) 3. Neutral to moderately alkaline (pH 6.5–8.5) 4. Strongly alkaline (pH > 8.5)		Various typomorphic water migrants: H^+; Al^{3+}; Fe^{2+}; Ca^{2+}; Na^+; K^+; SO_4^-; HCO_3^-; Cl^-; OH^-, etc.		Various content of organic compounds	
		21 water migration classes of the chemical elements (after A.I. Perel'man)								
IV	Properties of ground and glacial waters	1. Oxidising environment (available O_2) 2. Reductive gley environment (not available O_2 and without H_2S) 3. Hydrogen sulphide environment (not available O_2 and with H_2S)			1. Ultra acidic (pH < 3) 2. Acidic to moderately acidic (pH 3–6.5) 3. Neutral to moderately alkaline (pH 6.5–8.5) 4. Strongly alkaline (pH > 8.5)			Various typomorphic water migrants		
V	Properties of aerial migration	Subjected to aeolian (wind) erosion			Not subjected to aeolian (wind) erosion			Containing contemporary aeolian sediments		
VI	Permafrost properties	Without permafrost			Sporadic permafrost areas		Discontinuous permafrost areas	Continuous permafrost areas		
VII	Geomorphological properties	1. Plains 2. Lowlands and midlands 3. Highlands			Plains: 1. Eluvial 2. Trans-eluvial 3. Trans-accumulative 4. Trans-superaquatic			Eluvial: 1. Peak-topped 2. Flat-topped		
VIII	Properties of parent rocks	1. Sedimentary rocks 2. Magmatic rock 3. Intensively metamorphosed rocks			Sedimentary rocks: 1. Carbonaceous 2. Terrigenous 3. Carbonaceous and terrigenous		Carbonaceous rocks: 1. Limestones 2. Dolomites 3. Limestones with sideritic concretions	Limestones: 1. Silurian age, enriched with Pb 2. Devonian age, enriched with Mn, etc.		

to the classification at 1:500,000 scale, landscapes that include spoil tips are technogenic, agricultural, not amended, with rotation of annual crops, with hydrocarbonate-calciferous waters and oxidising soil environment (available O_2), not subjected to aeolian (wind) erosion, without permafrost, plain, trans-eluvial on terrigenous sedimentary rocks. Such landscapes occur widely in the Central and Southern Russia. More information about the geochemical maps can be found in Alekseenko et al. (2002).

Detailed large-scale studies allow finding small areas of biogenic steppe landscapes and technogenic forest plantations in close proximity to the spoil tips (10–200 m).

Spoil tips themselves, minor dumps, and fragments of steppes and forests are situated in the upper parts of slopes. Trans-eluvial landscapes dominate in the region, occupying vast territories.

Soil, plant and rock sampling accompanied geochemical mapping on a grid of 5 × 5–5 × 7 km. Landscape-geochemical conditions were described at each sampling point. Soil pits were investigated to study vertical geochemical profiles. All the samples were analysed for gross contents of 14–25 elements using emission spectral analysis.

Thus, geochemical anomalies were found in soils of Rostov Oblast by making use of the maps. The majority of the anomalies are correlated with coal mining areas. One of the most contrasting anomalies was described at the outskirts of Kamensk-Shakhtinsky town. Previous findings revealed the overlaying geochemical anomalies of Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Mo, Ba, and Pb in the area of 630 km^2 (Alekseenko et al., 2002). Therefore, the detailed soil sampling was performed here on a grid of 100 × 100 m; five soil cross sections were sampled consequently each 5 m at the spoil tips and each 80 m in surrounding areas. Additional soil pits were also studied at these spots. The total number of samples taken was over 11,000. A landscape-geochemical description was performed on each point; bedding rock and plant sampling was also conducted as far as possible. The biogeochemical survey included wormwood (*Artemisia austriaca*) and couch grass (*Elytrigia repens*) studying.

2.3. Soil types

The samples were taken from the uppermost soil horizon (0–10 cm), which is "the geochemical centre of soils" (Perel'man, 1986) with a critical intensity of geochemical processes in a landscape. It was also found that the main geochemical changes in the studied landscapes took place in this horizon. Similar results were obtained by previous research in analogous areas (Il'in et al., 2003; Tepanosyan et al., 2016; Timofeev and Kosheleva, 2016). The investigated mining site soils are recognised in the Classification and Diagnostic System of Russian Soils as *Technogenic Superficial Formations* (Shishov et al., 2004). According to the FAO World Reference Base for Soil Resources, they are *Technosols* (IUSS…, 2015). In *Technosols* the technical origin of soils prevails over their properties and pedogenesis (Rossiter, 2007). Soils of the surrounding agronomic landscapes that have been significantly altered by the agricultural activities are *Anthrosols* (IUSS…, 2015).

3. Methods

3.1. Analyses and control

The soil and plant samples were analysed for gross contents of Cu, Zn, Pb, Ag, Sn, Mo, Ba, Co, Ni, Mn, Ti, V, Cr, Ga, P, Li, Sr, Y, Yb, Nb, Sc, and Zr, in the certified and accredited Central Testing Laboratory at 'Kavkazgeolsyomka', by using emission spectral analysis. Silicon analyses were performed in averaged samples from each large geochemical landscape. Mineralogical, X-ray fluorescence and particle size analyses were carried out in samples taken direct at coal mining sites. Clay mineral detection was performed using an electron microscope, thermal analysis and dehydration.

The external control was conducted in the Common Use Centre of Mining University (X-ray fluorescence analysis) and Institute of Ore Geology, Petrography, Mineralogy, and Geochemistry of the Russian Academy of Sciences (neutron activation analyses). The results of analyses were subjected to standard statistical treatment. Almost all the calculations were made with a probability of 95%. The value of the random average relative deviation of contents did not exceed 1.4. An inner analyses (for 6% of the total number of samples) and external analyses controls (for 3% of the total number of samples) were conducted. Random and systematic errors showed high analyses repeatability and correctness.

The geobotanical survey was a special part of the work, describing typical vegetation communities for the investigated coal mining sites.

4. Results and discussion

The studied territory consists of agricultural lands and burnt-out spoil tips. Soils are formed in trans-eluvial landscapes with hydrocarbonate-calciferous waters on terrigenous Cretaceous deposits (Alekseenko et al., 2002). Such landscapes are abundant in the whole Rostov Oblast. The average background contents of chemical elements in soil cover and spoil tips are shown in Table 2. Background contents of Pb, Cu and Co in local soils used for agronomic activities exceed their abundances in the Earth's soil cover in 1.8, 2.1, and 2.4 times, respectively. On the other hand, background contents of Ba, Cr, Ga, Mn, Mo, Ti and V are lower than in the Earth's soil cover (Table 2). An established consistent pattern reflects geochemical characteristics of considered landscapes. Therefore, in order to avoid possible mistakes, it is reasonable to assess geochemical changes by comparing contents in soils of artificial landscapes with natural ones, but not with the abundances.

The residual steppe landscapes are situated in between agronomic landscapes at a several kilometers distance from spoil tips near Kamensk-Shakhtinsky town. Soils of these landscapes are not involved in agriculture, except for rare haymaking and cattle grazing. Several tree belt areas are also located there, planted at the time of coal mining. These landscapes cannot be considered as biogenic due to the significant geochemical impact by spoil tips. Patterns of element distribution in soils of agronomic and steppe landscapes surrounding the spoil tips are shown in Tables 2 and 3. As can be seen from the above data, the contents are slightly lower as compared with average contents in agronomic landscapes (except for Mo). This pattern can be considered as an evidence of certain soil pollution during agricultural use of landscapes.

Contents of Mn, Cu, V, Cr, Zn, Pb, Mo and Ba in soils of steppe landscapes surrounding spoil tips are higher than both in soils of remote steppe landscapes and in soils of agronomic landscapes, that correlates with the findings of Pavolová et al. (2016). This allows to state that the geochemical impact of spoil tips at the 1–2 km distance is much greater than that caused by agriculture.

Geochemical transformation of soils triggered by mine waste stacking occurs not only in the upper horizons but also in the whole soil profiles. This phenomenon is clearly seen when comparing geochemical anomalies of Cr, Mo and Zn in soil profiles in the same agronomic landscape at different distances from spoil tips. (Fig. 2a, b) shows data on vertical element distribution in soil profiles of all the studied landscapes. Contents of Cr, Mo and Zn are averagely twice heightened in the topsoil.

A plant cover is practically absent over the upper parts of the burning spoil tips where self-ignition generally occurs (Photo 1). Few individuals of synanthropic annual plants (*Centaurea diffusa* Lam., *Conyza canadensis* (L.) Cronq., *Ambrosia artemisiifolia* L.) were found (Table 4a). This is related both to phytotoxicity of spoil tip and to the atmospheric air pollution by ignition products.

A lack of vegetation, as well as continuous entrance of ignition

Table 2
Abundances in the Earth's soil cover and average contents (mg/kg) of the chemical elements in soil cover and spoil tips of coal mining area in Rostov Oblast, Russia.

Elements	Abundance in the Earth's soil cover[a]	Agronomic landscapes	Residual steppe landscapes near the spoil tips	Steppe landscapes directly adjoining the spoil tips	Water-logged spoil tips	Surface layers of the burnt-out spoil tips	Content gradient in vertical profile at spoil tips
Ba	500	470 / 460 – 550[b]	430	620	2000	670	800–1000
Co	8	19 / 13 – 23	18	18	10	–	–
Cr	200	71 / 68 – 87	53	90	60	–	–
Cu	20	41 / 40 – 48	32	57	30	65	50–400
Ga	30	16 / 15 – 20	10	11	15	–	–
Mn	850	602 / 480 – 900	560	980	1000	400	–
Mo	2	1.0 / 1.0 – 1.5	5	3	3	4.8	2–15
Ni	40	43 / 42 – 50	35	41	20	–	–
Pb	10	18 / 17 – 27	16	29	30	41	30–60
Ti	4600	4550 / 3330 – 4580	4060	4460	5000	–	–
V	100	98 / 78 – 106	68	128	100	–	–
Zn	50	51 / 50 – 66	13	65	30	–	–

[a] The averaged content of the elements in the Earth's soils, after A.P. Vinogradov (1959).
[b] The arithmetic mean (underlined), minimum and maximum.

Table 3
Chemical element distribution in soils of agronomic and steppe landscapes directly adjoining the spoil tips in Rostov Oblast, Russia.

Element	Distribution	Arithmetic mean contents, mg/kg	Median contents, mg/g	Standard deviation	Standard error of mean	Anomalous contents in correlating samples, mg/kg		
						9 samples	2–3 samples	Single samples
Agronomic landscapes								
Mn	Log-normal	614	602	1.21	1.8	730	885	1072
Ni	Normal	44	43	0.75	0.1	51	58	66
Cu	Normal	41	41	1	0.1	51	61	71
Ti	Log-normal	4654	4551	1.24	13.2	5647	7008	8698
V	Log-normal	100	98	1.19	0.2	117	141	168
Cr	Normal	71	71	1.6	0.2	87	102	119
Zn	Log-normal	53	51	1.29	0.1	66	85	110
Pb	Log-normal	19	18	1.48	0.1	27	40	60
Co	Log-normal	19	19	1.2	0.004	23	28	33
Mo	Normal	1	1	0.06	0.009	2	2.6	3.2
Ba	Log-normal	498	470	1.39	2.6	653	408	1262
Ga	Normal	16	16	0.3	0.05	19	22	25
Steppe landscapes directly adjoining the spoil tips								
Mn	Log-normal	1021	983	1.31	5.8	1294.3	1704.8	2245.6
Ni	Normal	41	41	1.67	0.3	58.1	74.8	91.5
Cu	Normal	51	51	1.39	0.26	64.6	78.5	92.4
Ti	Normal	4464	4464	69.29	13.09	5157	5850.1	6543
V	Normal	128	128	3.67	0.69	164.9	201.6	238.3
Cr	Not found	90	–	–	–	–	–	180.8
Zn	Log-normal	71	65	1.51	0.66	98	148	223.9
Zr	Normal	151	151	8.13	1.53	23.2	31.4	39.5
Pb	Normal	29	29	1.22	0.23	41.5	53.7	65.9
Co	Normal	18	18	0.32	0.06	20.9	24.1	27.3
Mo	Normal	3	3	0.21	0.039	4.6	6.7	8.8
Ba	Normal	618	618	16.34	3.088	781.3	944.7	1108.1
Ga	Normal	11	11	1.31	5.8	196	278	36
Sr	Normal	152	152	1.67	0.3	195.9	240	284.1

products from the waste heaps into the atmosphere and temperature differential near burning tips, contribute to soil pollution in the surrounding landscapes at this stage of coal waste storage.

Several spoil tips are flooded in order to prevent ignition processes. As a result, a peculiar kind of water bodies is formed over their levelled surface (Photo 2). However, even under these conditions longing for decades, soil-forming processes do not occur. Solitary plants are found only at the borders of such impoundments (Table 4, c). Vegetation cover virtually does not exist for a long time at spoil tips even after flooding cancellation. Contents of Cu, Pb, As, Mo, Ba, Co, Mn, V, Li, Sr, and Cd in surface layers of the flooded spoil tips exceed the respective abundances in the Earth's soil cover. The greatest exceedances over abundances are characteristic of Ba, Cd, and Pb, 3–4 times on the average. Contents of such elements as Zn, Ag, Sn, Ni, Cr, P, Ga, and Ge in surface layers of flooded tips are lower as compared with the respective abundances in the Earth's soil cover.

It is considered that the flooded spoil tips could be sources of anomalous chemical element contents in soils of surrounding landscapes. Tables 2 and 3 show the contents of Ba, Pb, Mn, Ti and V (1.1–4.7 times higher in spoils), which indicates that in the tip sides and the surface around the artificial reservoir the contents of these elements are higher than in the soils of the surrounding landscapes. Furthermore, contents of Ba, Pb, Zn, and Mo in some cases are not only abnormal but refer to outlier ones. Contents of Cr, Ga, Mo, and Zn are often anomalous only in soils of field crops or in soils of steppe landscapes (Tables 2 and 3). The average contents of Cu, Co, and Ni in flooded spoil tips are lower than in soils of surrounding landscapes. The vegetation cover at the shores of artificial lakes, formed after flooding the surface of spoil tips, is represented by mono-dominant phytocenoses *Phragmites australis* (Cav.) Trin ex Steud with a minimal number of related species (4–6). The vitality level of coenopopulation is high: the height of the reed plants reaches 2–4 m, the density is about 30–80 shoots per m^2 and the length in ecotopes varies within 10–50 m (Photo 2), which indicates the successful species' adaptation to phytotoxic medium at artificial reservoirs and dumps in the investigated area.

The polydominant ruderal community with single trees and shrubs of the local (*Betula pendula* Roth., *Pyrus caucasica* Fed., *Rosa canina* L., *Swida australis* (C.A. Mey.) Pojark. ex Grossh.) and the introduced flora (*Robinia pseudoacacia* L. *Prunus armeniaca* L.) are found near the dried reservoirs on their flat surface of slopes and along the dump edges (Table 4d). The invasive *Robinia pseudoacacia* species seemed to be the most adapted to the conditions of coal dumps, showing high vitality and population abundance, as well as the ability of expansion around the disturbed area. Up to 35 species of vascular plants were recorded consisting the low-species communities. The projected coverage varies depending on the density of the substrate (5–80%). Steppe, meadow and synanthropic species are at the heart of grass canopy making up to 30% of the floristic community composition. Stratification of phytocenoses is weak as vegetation is mainly a sparse mosaic of individual groups in micro-depressions on the flat parts and gentle slopes of dumps. The moss-lichen floor is missing due to the low water capacity of the substrate (Bolshunova et al., 2014; Pashkevich and Petrova, 2015). The plant vitality is reduced; some species show signs of strengthening xeromorphism (*Phragmites australis* (Cav.) Trin ex Steudel, *Cynanchum acutum* L., and others), fasciations and teratomas of generative organs (*Cichorium intybus* L.).

Thus, the burning spoil tips, as well as the flooded ones with existing and parched man-made reservoirs on their upper parts, still represent negative geochemical effects on the soils of the surrounding landscapes.

Soils have not formed yet on spoil tips that had been burnt > 30 years ago (i.e., spoil tips exist for > 50–70 years). This is confirmed by the composition of mine wastes that make the spoil tips and by the fact that there are some individual instances of steppe vegetation (Table 4b) on their surface at several spots only. Burnt spoil tips still have an impact on the soils of surrounding landscapes. The air within the 1 km radius from tips contains dust contents exceeding TAC (threshold allowable content). Dust content in the air even at the 3.5 $m\,s^{-1}$ wind speed and at 90% relative humidity is up to 10–15 $mg\,m^{-3}$ at the 150 m distance from tips (Pashkevich, 2017). The adhering dust alters the composition of steppe soils. In addition, burnt spoil tips sometimes

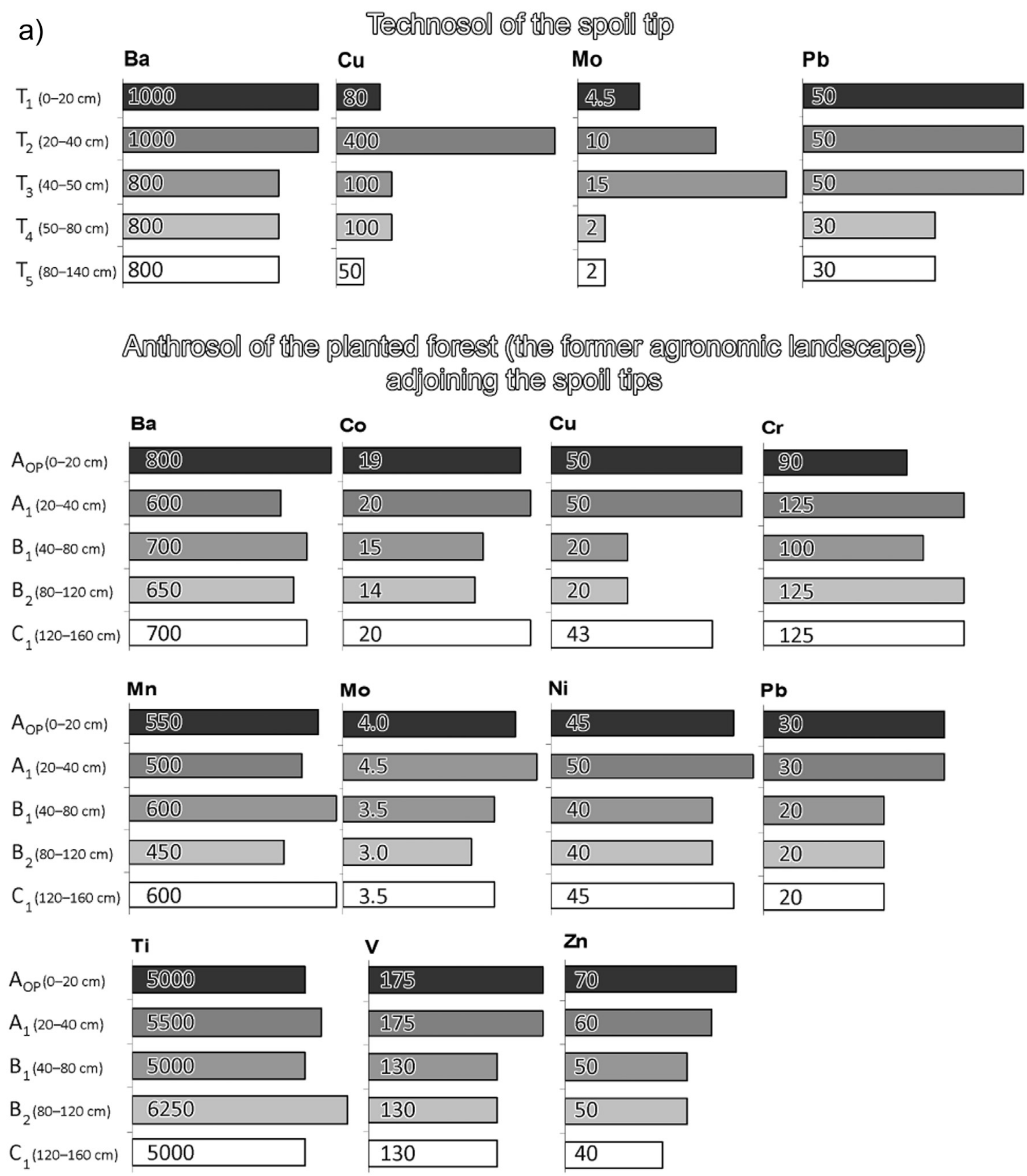

Fig. 2. a. Chemical element contents in vertical soil profiles (mg/kg). Horizons of the Technosol of the spoil tip: T_1 0–2 cm, T_2 20–40 cm, T_3 40–50 cm, T_4 50–80 cm, T_5 80–140 cm. Horizons of the Anthrosol of the planted forest adjoining the spoil tips: A_{OP} 0–20 cm (the old ploughing horizon), A_1 20–40 cm, B_1 40–80 cm, B_2 80–120 cm, C_1 120–160 cm.
b. Chemical element contents in vertical soil profiles (mg/kg). Horizons of the Anthrosol of the agronomic landscape 2 km away from the spoil tips: A_P 0–40 cm (the ploughing horizon), B_1 40–60 cm, B_2 60–110 cm, C_1 110–120 cm, C_2 120–160 cm. Horizons of the Anthrosol of the agronomic landscape in the low-contrast anomalies of Cr, Mo, and Zn adjoining the spoil tips: A_P 0–40 cm (the ploughing horizon), B_1 40–70 cm, B_2 70–100 cm, C_1 100–120 cm.

become sources of mudslides under the influence of rain, destroying the surrounding soil cover at the distance up to 1 km.

The soil cover has not finally formed on the spoil tips burnt > 50 years ago. However, mineralogical composition, amount and size of the debris on the surface of spoil tips have noticeably changed comparing with rocks which initially formed the spoil tips.

For instance, the debris > 5 mm in most cases represent 40–64% of the soil composition at the burnt spoil tips (instead of 80–90% initially existed),

After removing the debris > 5 mm, the fraction > 0.25 mm represents 42.5–43.0% of the residual sample. This fraction content is not much more than in the steppe soils surrounding the spoil tips: 36.8% on the average (Table 5). After removing the debris > 5 mm, a fraction smaller than 0.1 mm represents 16–43% and < 0.07 mm represents 28–32% at the burnt spoil tips. Thus, the ratio between fine fractions in rock weathering products of the burnt spoil tips is close to the values in the steppe soils (Table 5).

Mineralogical analysis of the fine fraction - electron microscopy, dehydration methods and thermic ray analyzes - showed that it mainly consists of kaolinite, quartz and hydromicas, sometimes traces of gypsum and chlorite appear in its composition (24 samples were subjected to a detailed analysis). Rock debris, enclosing substantially carbonaceous shale, predominate in the composition of the fraction larger than 1 mm.

However, the data were obtained after removing massive debris that represent almost a half of the weight in samples from the spoil tips,

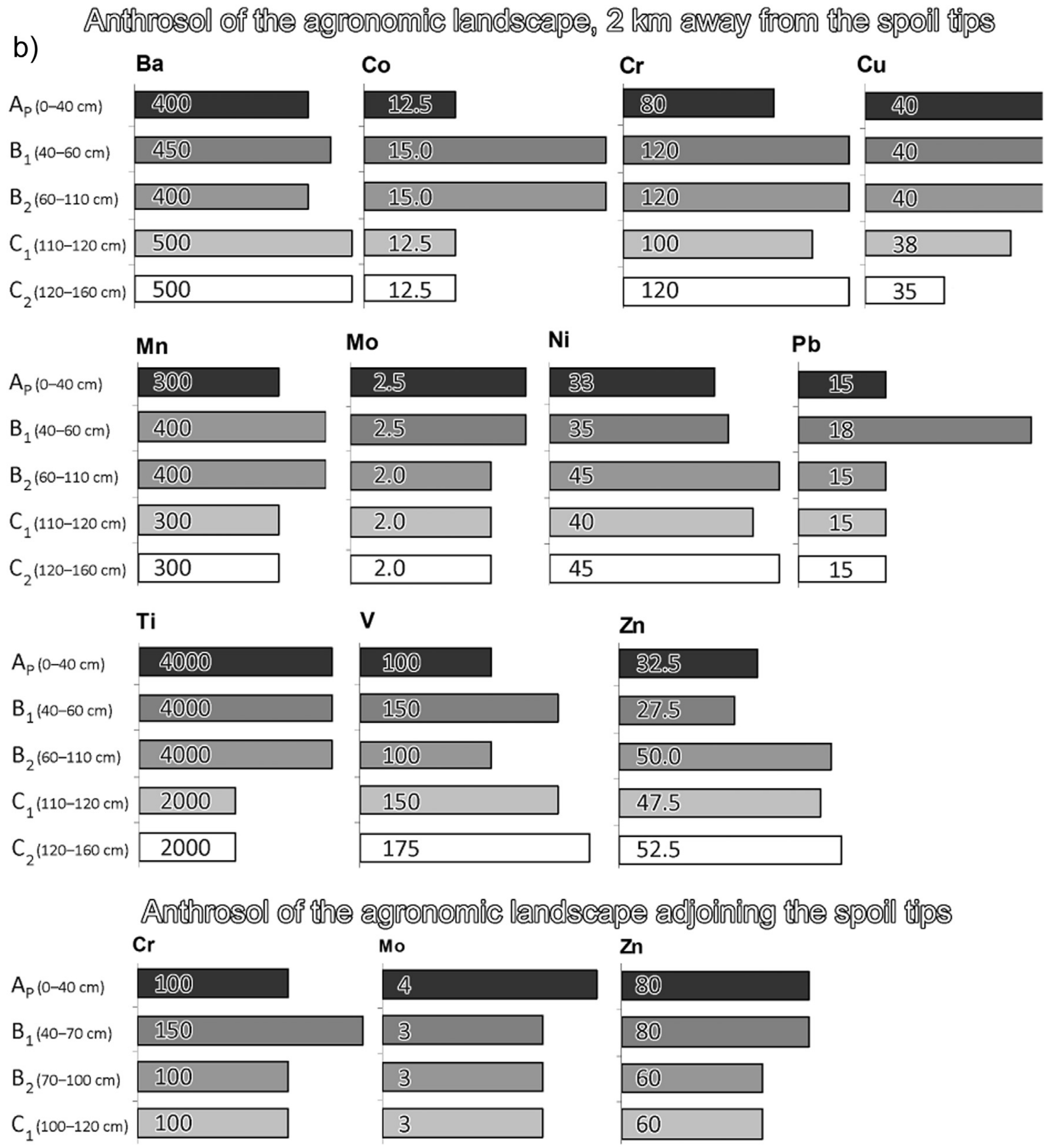

Fig. 2. (*continued*)

Table 4
Plants growing on dumps and spoil tips of coal mines in Rostov Oblast, Russia.

Ecotopes	Dominant and co-dominant species of vegetation communities
a) Upper parts of spoil tips (self-ignition areas)	*Centaurea diffusa Lam.*[a], *Conyza canadensis* (*L.*) *Cronq.*[b], *Ambrosia artemisiifolia L.*[b]
b) Burnt-out spoil tips	*Artemisia austriaca Jacq.*[a], *Ambrosia artemisiifolia L.*[b], *Phragmites australis* (*Cav.*) *Trin ex Steudel*[a], *Centaurea diffusa Lam.*[a], *Conyza canadensis* (*L.*) *Cronq.*[b]
c) Coastlines of artificial water bodies	*Phragmites australis* (*Cav.*) *Trin ex Steudel*[a], *Cynanchum acutum L.*[a], *Ambrosia artemisiifolia L.*[b], *Lactuca serriola Torner*[b], *Euphorbia virgata Waldst. and Kit.*[a], *Cichorium intybus L.*[a]
d) Surrounding areas of dried-up water bodies in the upper parts of spoil tips	*Robinia pseudoacacia L.*[b], *Betula pendula Roth.*[b], *Pyrus caucasica Fed.*[a], *Prunus armeniaca L.*[b], *Rosa canina L.*[a], *Swida australis* (*C.A. Mey.*) *Pojark. ex Grossh.*[a], *Artemisia absinthium L.*[a], *A. austriaca Jacq.*[a], *A. vulgaris L.*[a], *Phragmites australis* (*Cav.*) *Trin ex Steudel*[a], *Ambrosia artemisiifolia L.*[b], *Cichorium intybus L.*[a], *Centaurea diffusa Lam.*[a], *Cynanchum acutum L.*[a], *Achillea millefolium L.*[a], *Lactuca serriola Torner*[b]

[a] Native species, typical of the local zonal and azonal communities.
[b] Synanthropic species, including adventitious species.

Photo 2. A water pond on the levelled surface of spoil tip (*Phragmites australis* plants are shown by an arrow).

Table 5
Average fraction contents in the steppe soils around coal mining area in Rostov Oblast, Russia (wt% after removing debris > 5 mm from the samples).

Transect	Fine fractions		
	> 0.25 mm	0.25–0.1 mm	< 0.1
1	38.5	26.0	35.5
2	29.8	40.9	29.3
3	37.1	44.1	18.8
4	38.0	23.5	34.5
5	37.0	28.1	34.9
Average	36.8	32.6	30.6

while in the surrounding steppe soils represent < 10% of the soil composition.

First, this is an evidence of a very substantial disintegration of rock fragments in the spoil tips. Secondly, rock weathering of debris makes the ratios between fractions in the tips similar to the numbers in the adjoining natural soils.

The mineral composition of soils at the spoil tips and adjoining areas (Table 6). The colloid-dispersed fraction of the spoil tips contains gypsum, kaolinite, quartz and chlorite. Chlorite is found at the distance up to 70 m from the tip border. Hydromicas, kaolinite, halloysite and montmorillonite are contained in this fraction independently on the distance from the tips.

The fraction 0.07–0.10 mm of the spoil tips and surrounding soils contains fragments of rocks, coal, quartz grains, feldspars, bunches of Fe hydroxides, grains and grain fragments of sphene, rutile, zircon, tourmaline, grenade, and biotite flakes. Oxidized pyrite is found at the distance up to 70 m, fragments of chlorite grains are at the distance up to 100 m from the contact zone with the tips. The fraction 0.10–1.0 mm contains rock debris, coal, quartz, slag, hydromicas, gypsum, muscovite and kaolinite. Hydromicas in all the fractions are made of flake formations, clots, slightly elongated and rounded scales. Kaolinite is mainly presented as pseudohexagonal crystals; halloysite has an elongated rod-shaped form.

Judging by the mineralogical and geochemical properties of the studied samples, a wave of acid element leaching, associated with decomposing sulphides, has practically finished in the last 70 years i.e. oxidized pyrite grains are found rarely (Table 6) that is supported by the findings of Nesbitt (1998) and Tiwary (2001). Negative anomalies usually develop in soils around a spoil tip with the acid leaching (Fernandez and Borrok, 2009; Fortin et al., 1995). Based upon the Table 2, the decreased Co, Ga and Ni contents can be considered as consequences of such a process. Nevertheless, the elevated Ba, Cr, Cu, Mn, Mo, Pb, V and Zn contents are found in soils affected be the neighbouring spoil tips. These conclusions correlate also with the findings in some regions of Bangladesh and China (Bhuiyan et al., 2010; Hu et al., 2009).

A large number of rock debris and presence of feldspars in topsoils allow to state that rock weathering is unfinished in spoil tips. This fact along with mineralogical differences from surrounding soils and virtually full absence of plants indicate that soil formation is at its early stages in the spoil tips.

A study of geochemical characteristics of loose (still unconsolidated) rocks, forming a surface of the burnt spoil tips, showed that the content of several metals was different from the content in the flooded spoil tips and soils of surrounding steppes. The most significant are Thus, the increased average contents of Cu, Mo and Pb in the areas directly affected by the rejects (Table 2). It should be admitted that the contents of Zn and Cu have considerably increased and became higher than the abundances in the Earth's soil cover. The contents of Ni and Co have slightly (1.5 times) increased. In the other hand, some contents have decreased; this was the case of the Mg (from 1000 to 400 mg/kg) and Ba (from 2000 to 670 mg/kg).

The vertical profile distribution was studied for chemical elements, which contents in the surface deposits of burnt spoil tips exceeded those in the flooded tips and in the surrounding soils (Cu, Mo, and Pb). The experiment was also conducted for Ba, as its content in the burnt spoil tips was higher than in the soils of surrounding landscapes, although it was less than in flooded spoil tips (Table 2). The content of Ba decreases starting only from the 35 cm depth. Contents of the rest of the studied elements unevenly increased with depth, reaching a maximum at a distance from the surface at intervals of 50–70 cm for Mo, 30–50 cm for Cu, and up to 90 cm for Pb. The maximum content of Ba is observed from the surface to a depth of 30 cm.

It should be especially noted that even a minimum content of the investigated elements exceeds the abundances and average contents in soils of the surrounding landscapes, wherein in the vertical geochemical profile. Consequently, the demolition of burnt soil tips' material leads to technogenic soil pollution and to the formation of the above-mentioned geochemical anomalies in the Kamensk-Shakhtinskiy area. Some low-contrast of Pb and Zn anomalies, in relation to the contents in background landscape soils, with the highest content of both metals in the fine fractions, were revealed directly in the area of spoil tips. Similar results were obtained by the researches in the Tomsk Region (Zhornyak

Table 6
Mineral composition of various soil fractions in the spoil tips and surrounding steppe landscapes.

Spoil tips	Surrounding areas at the distance of		Regardless of the distance
	40–70 m	100 m	
I. Colloid-dispersed fraction			
Gypsum, kaolinite, quartz and chlorite	Chlorite	–	Hydromicas, kaolinite, halloysite and montmorillonite
II. Fraction 0.07–0.10 mm			
Rock debris	Oxidized pyrite	Fragments of chlorite grains	Fragments of rocks, coal, quartz grains, feldspars; bunches of Fe hydroxides; grains and grain fragments of sphene, rutile, zircon, tourmaline, grenade; biotite flakes
III. Fractions 0.10–0.25 mm; 0.25–0.50 mm; 0.5–1.0 mm			
Rock debris (siltstones, carbonaceous shales, mudstones, sandstones), coal, quartz, slag, hydromicas, gypsum, muscovite and kaolinite			

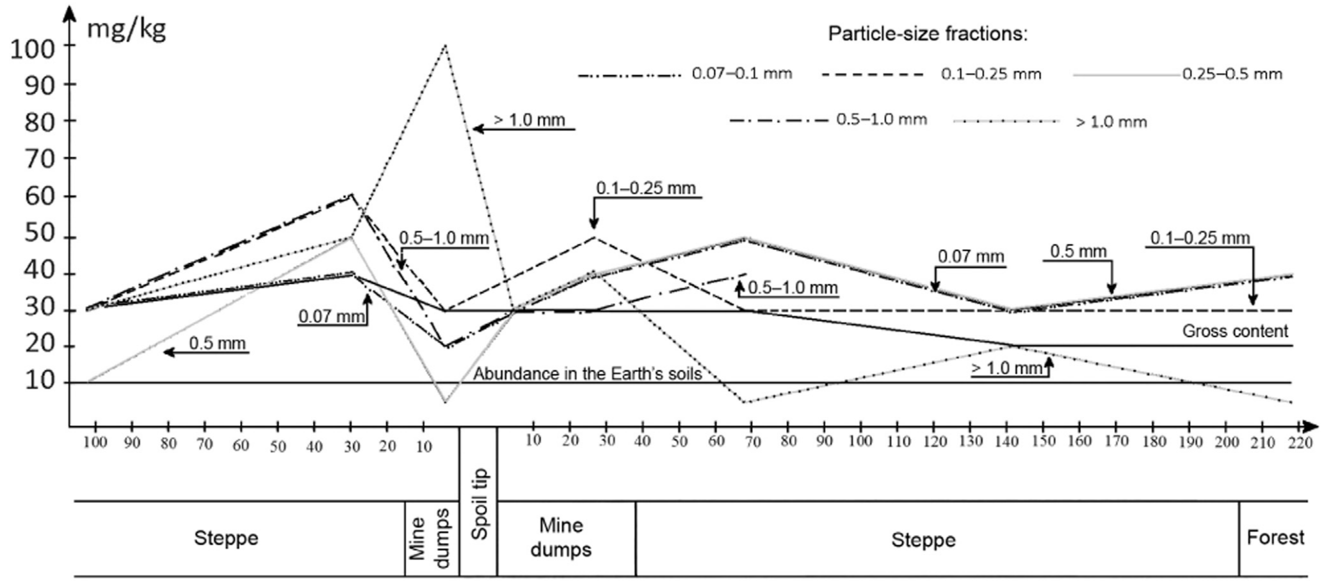

Fig. 3. The generalised graph of *Pb* content changing in different particle-size fractions of steppe soils after 50–80 years of the spoil tip influence.

Photo 3. Flooding of slumped depression areas over the mined layers.

et al., 2016). Fig. 3 may indicate the fact that the anomaly formation is associated with material erosion from the burnt spoil tips. As can be seen from the figure, the changes occurred not only in the total content but also in the individual fraction of soils.

Since the soil formation process is closely linked to the development of vegetation, we note that the number of plant population on burnt spoil tips increase as compared to those burning and flooded. However, projective cover (0–15%) and species diversity of phytocoenosis (3–5) remain very low, which prevents a flow of any soil-forming process. The coefficient of bioaccumulation is calculated as the average element contents in the ash of the Austrian wormwood (*Artemisia austriaca*) related to the average element contents in soil. Their values in agronomic values are 0.3 for V, 2.5 for Mn, 0.6 for Ni, 1.4 for Cu and 0.5 for Zn. The data obtained by Syso et al. (2016) support these findings and underline the technogenic influence of the soil tips.

It is observed the formation of ruderal phytocenoses that involves 10–15% of native flora species, as well as invasive and introduced plants, in the ecotopes of spoil tips, influenced by some environmental factors. Communities, formed in this way, have simple structure, low species diversity, as well as the presence of anomalies in plant development: fasciations and teratomas.

Ground settling usually followed by flooding of valleys with acidic waters is very frequently observed over the areas with the extracted rocks. Karthe et al. (2015) and Strakhovenko et al. (2016) describe several examples of the technogenic impact on water streams and bodies caused by mining and other human activities. It can be found a kind of lakes forms at the area up to 3000 m^2 (Photo 3) where a self-restoration of soils does not occur.

5. Conclusions

1. In the investigated area, mining leads to soil destruction within the territory directly occupied by the spoil tips and adjacent dumps of rocks, as well as on the subsidence areas, with often-formed lakes. A soil cover has not yet finally formed following a self-restoration on the spoil tips aged > 50–70 years and burnt-out decades ago. A vegetation cover, which emerged during this time range, practically does not support the progress of any considerable soil-forming process.
2. The impounded water bodies, formed as a consequence of flooding at the burning spoil tips, barely contribute to the plant growth and substantially do not cause the soil development.
3. The surface layers of the spoil tips at all stages of their development are different from the surrounding steppe soils in geochemical characteristics and mineralogical composition. The soil sampled in the area directly affected by the coal mining activities is characterised by the heightened contents of *Mn*, *Cu*, *V*, *Cr*, *Zn*, *Pb*, *Mo* and *Ba* and occurrence of oxidized pyrite, coal, chlorite, quartz, slag, hydromicas, gypsum, muscovite and kaolinite that are not typical of the areas above the mining sites.
4. The atmospheric and water inflow of material from the spoil tips changes (in the cases studied – worsens) a state of the steppe soils within a radius of 1 km, and leads to the increase in some heavy metal content in these soils.

Acknowledgments

The analyses were performed using the equipment of the Common Use Centre of Saint Petersburg Mining University. The authors would like to thank the editor and two anonymous reviewers for their constructive comments, which highly improved the manuscript.

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