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RESEARCH ARTICLE

Element mobility from the copper smelting slag recycling waste into forest soils of the taiga in Middle Urals

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Abstract

The article presents the results of assessing the element mobility (chemical elements and compounds) from the copper smelting slag recycling waste into brown forest soils (Haplic Cambisols) of the southern taiga district in Middle Urals, Russia. The copper smelting slag recycling waste was obtained by crushing the cast slag of the Sredneuralskiy Smelter ("technical sand") followed by flotation extraction of copper concentrate. The investigations were carried out in two forest types, distinguished according to the principles of the genetic forest typology, cowberry shrub pine forest and berry pine forest with linden, and the corresponding clear-cuttings. We conducted the experiment in the autumn before the snow cover was established in two variants: (i) we evenly scattered 1 kg of waste on meter sample plots; (ii) we weighed the "technical sand" by 100 g, packed it in non-woven material and buried it in the soil to a depth of 7–10 cm. Two years later, we dug up the bags with waste and weighed them. The analyses were performed by inductively coupled plasma mass spectrometry using Elan-9000 ICP mass spectrometer. As a result of the research, it was found that waste loses 11% mass over 2 years of being in forest soils. The content of Zn, As, Cd, and Se changes most strongly. The difference in the degree of element migration from the "technical sand" to the brown forest soils of the two forest types and clear-cuttings was revealed. The study of the effect of technogenic waste on the dominant and diagnostic species of grassy vegetation in the selected forest ecosystems of the Middle Urals was carried out. There was no negative effect on the qualitative composition of the grassy layer of two forest types and their clear-cuttings after 1 year after a single surface application of mineral waste at a concentration of 1 kg/m^2.

Keywords Copper smelting slag · Element migration · Forest soils · Mineral waste · Environmental biogeochemistry · Taiga

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Introduction

Waste from mining and metallurgical production is the cause of serious changes in natural ecosystems. They lead to landscape disruption, pollute the environment, and transform the biogeochemical cycles (Becker et al. 2019; Gabarrón et al. 2019). Currently, the general direction of research on technogenic formations is focused on evaluating them as a potential source of mineral resources (Mikoda et al. 2018; Naumov and Naumova 2019) and building materials (Singh and Singh 2019). With increasing attention to environmental risk factors, research on migration of industrial waste components to the soil and water has intensified (Kierczak et al. 2013; Sun et al. 2016; Ettler et al. 2016; Tyszka et al. 2016; Matanzas et al. 2017; Tarasenko et al. 2017; Potysz et al. 2017; Zolotova and Ryabinin 2019; Wang et al. 2020). In this research, the focus is on the mobilization of chemical elements that are toxic to the natural environment. Few studies are devoted to assessing the impact of metallurgical wastes on the floristic composition and productivity of plants (Turisová et al. 2016), as well as on the population of living organisms, for example, earthworm community (Mariet et al. 2020) and rhizosphere microbial communities (Agnello et al. 2018).

The activities of smelters are accompanied by the formation of dumps of cast or granulated slag. They contain large amounts of heavy metals and pose a serious threat to the ecology of the regions; hence, studies of old and modern pyrometallurgical copper slags dumps are carried out. Scientists investigated the mineralogical and chemical composition of copper slags (Kierczak et al. 2013; Zolotova and Ryabinin 2019; Erokhin et al. 2019) and the migration of elements from slag into soils (Kierczak et al. 2013; Sun et al. 2016; Tyszka et al. 2016; Agnello et al. 2018), river deposits (Kierczak et al. 2013), ground and surface water (Kierczak et al. 2013), and also into plants (Sun et al. 2016; Agnello et al. 2018; Zolotova and Ryabinin 2019). Leaching of non-ferrous metals from copper smelting slag using acidophilic organisms deserves attention (Muravyov and Fomchenko 2013).

In Russia, the first successful attempts to process dump cast slag as an unconventional source of copper date back to the 1990s of the twentieth century. The technology consists in grinding cast slag followed by flotation extraction of copper concentrate (Sredneuralskiy smelter (SUMZ), Kirovograd smelter, Karabash smelter (Karabashmed)). The resulting copper concentrate with a solid content of 50–60% and a copper concentration of 10 to 25% through pipelines enters the batching department of the copper smelter, and magnetite-containing sands are filtered and stored in dry dumps—open storage warehouses (Makarov et al. 2010).

The copper smelting slag recycling waste ("technical sand") is a finely dispersed material with a dimension of 0.05 mm, and its properties are poorly understood (Kotelnikova and Ryabinin 2018). The contents of Cu, Zn, Pb, As, Sn, Cr, Mo, and Cd in "technical sand" are high enough and pose a potential threat to the environment. To date, only the Sredneuralsk copper smelter has accumulated about 20 million tons of copper smelting slag recycling waste. The waste mineral composition largely determines their properties, including the migration activity of components. Technical sand consists of fayalite, 49%; quartz, 20%; magnetite, 10%; zinc ferrite, 8%; pyrrhotite, 1%; bornite, 0.5%; chalcopyrite, 0.4%; covellin, 0.05%; and others, 11.05% (Guman et al. 2010). Previously, the mobility of the Zn and Cu of copper smelting slag recycling waste of SUMZ during leaching under model hypergenic conditions (Kotelnikova 2010; Reutov et al. 2015) and the element migration into aqueous solutions (Kotelnikova 2008; Guman et al. 2010) were studied. The copper smelting slag recycling waste of "SUMZ" is classified as hazard class IV according to the sanitary and epidemiological conclusion of May 11, 2004, and hazard class V (lower hazard class) according to the results of the environmental impact assessment of the Interregional Territorial Administration of Rostekhnadzor in the Urals Federal District of August 31, 2006.

The introduction of the copper smelting slag recycling waste into the soil profile of natural ecosystems would solve the extremely urgent task of its safe disposal. However, first having gaps in knowledge about this waste should be filled. The direction of the transformation processes of technical sand in the weathering zone, the composition of its products obtained, the degree of element mobility from slag to soil, their participation in biogeochemical cycles, as well as the effect of waste on the natural ecosystem sustainability in general and on their components in particular should be studied.

Forests are self-regulating ecological systems and play a leading role in compensating for anthropogenic environmental pressures. It is known that there is a positive relationship between the forest stability and biodiversity (Evseeva 2018). However, the anthropogenic impact on forest often leads to the opposite effect: an increase in biodiversity and at the same time a decrease in sustainability (Aleshchenko and Bukvareva 2010). In addition, the fact of loss of system stability with increasing complexity has been established by the method of mathematical modeling (Lankin et al. 2012; Soukhovolsky and Ivanova 2018). This contradiction indicates a lack of knowledge regarding the processes of interaction of ecosystems and the anthroposphere, which justifies the relevance of further studies of this problem.

In this research, a field experiment (controlled trial) was established. A metered amount of technogenic material of known chemical and mineral composition was introduced into the environmental conditions of a particular landscape, located at a sufficient distance from industrial zones and having forest typological, age, and other characteristics in a well-defined framework. The aim of the research at first stage was to assess the element mobility from the copper smelting slag recycling waste into brown forest soils under a forest canopy and in clear-cutting site. The effect of technogenic waste on the dominant and diagnostic species of grassy vegetation of selected forest ecosystems was evaluated.

Investigation area and method

Investigation area

The field experiment was set up in forest ecosystems of the Trans-Ural hilly-foothill province of the Sverdlovsk Region (57° 00′–57° 05′ N and 60° 15′–60° 25′ E) in Middle Urals, Russia (Fig. 1). The investigation area is a dissected foothill formed by the alternation of meridional highlands and ridges with wide intermountain extended depressions, in which large lakes surrounded by peat bogs are located (Kolesnikov et al. 1973). The investigation area is 200–500 m above sea level. Hills have soft outlines and blunt and wide peaks. The slopes

Fig. 1 Study area on the map of Russia (the origin map is posted on the site: http://russia-karta.ru/)

are long and gentle. The climate is moderately cold and humid. The frost-free period is 90–115 days, the average annual temperature is + 10 °C, and the snow cover is 40–50 cm (Kolesnikov et al. 1973).

The main factors of soil formation in the Urals are the mountainous terrain, continental climate, and wide distribution of both ancient and young parent rocks, which, in combination with vegetation, determine the great diversity of the soil cover. The mountain soils of the Middle Urals are characterized by a relatively small thickness, light mechanical composition (sandy, light, and medium loams), and varying degrees of crushed stone, which increases with decreasing soil thickness (Kolesnikov et al. 1973).

The investigations were performed on permanent sample plots (0.25–0.5 ha) in two forest types of Trans-Ural hilly-foothill province, cowberry shrub pine forests and berry pine forests with linden, and the corresponding clear-cuttings. These forest types differ in the position in the relief and the moisture mode. In the investigation area, forest types are identified according to the principles of genetic forest typology and the cadastre of forest types in the Sverdlovsk region (Kolesnikov et al. 1973), and the soil types are given according to Firsova's classification (Firsova 1977). The type of soil according to the WRB classification is shown in parentheses. The detailed studies of woody species and vegetation, soil morphology, and properties were carried on these sample plots earlier (Ivanova and Zolotova 2011, 2013; Zolotova and Ivanova 2012; Zolotova 2013).

The cowberry shrub pine forests (Fig. 2) grow on the tops and upper halves of the hillsides. Underdeveloped and typical brown forest soils (Haplic Cambisols) with a small thickness of the soil profile (less than 40 cm), light mechanical composition, and a high degree of crushed stone are typical of these habitats. The soils have a weakly acid reaction of water extract (pH = 5.10) and a strongly acid reaction of salt extraction (pH_{KCl} = 4.06), which do not change horizontally. The content of easily movable potassium (K_2O) in the humus horizon is rather high (292.5 mg/kg) but decreases sharply down the profile (Zolotova 2013). The cowberry shrub pine forests are distinguished by a low species diversity of higher plants, a sparse low-growing grass-shrub layer, and abundant natural regeneration of Scots pine (*P. sylvestris* L.). The tree layer is represented by one species, i.e., Scots pine. Birch trees (*Betula pubescens* Ehrh., *B. pendula* Roth) are scarce. In the ecological and floristic classification, the cowberry-pine forests belong to the class Vaccinio-Piceetea Br.-Bl. 1939 (boreal coniferous and light coniferous forests) of the alliance Dicrano-Pinion Matusk. 1962 (Ivanova and Zolotova 2013).

The upper parts of the near-valley slopes and peaks of low hills of Trans-Ural hilly-foothill province are characterized by typical brown forest soils (Haplic Cambisols) with poor profile differentiation into genetic horizons, small thickness (about 50 cm), and light mechanical composition. The soil color is dominated by brown tones, and the intensity of which decreases with depth. They have a weakly acid reaction of water extract (pH = 5.24) and a very strongly acid reaction of salt extraction (pH_{KCl} = 3.95). These soils are characterized by a high content of easily movable potassium (245 mg/kg), which sharply decreases down the profile (Zolotova 2013).

The berry pine forests with linden (Fig. 2) grow on the upper parts of the near-valley slopes and peaks of low hills of Trans-Ural hilly-foothill province. The first layer (canopy) of conditionally indigenous forests is represented by Scots pine and single birch trees (*B. pubescens*, *B. pendula*), and the second layer (lower canopy trees) forms *Tilia cordata* Mill. Predominant species in the grass-shrub layer are *Vaccinium myrtillus* L., *Vaccinium vitis-idaea* L., *Calamagrostis arundinacea* L. (Roth.). The berry pine forests with linden have features of the class Vaccinio-Piceetea (high constancy of *Vaccinium myrtillus*, *V. vitis-idaea*, the presence of *Picea obovata* Ledeb.), the class Brachypodio Pinnati-Betuletea pendulae (hemiboreal light-coniferous-small-

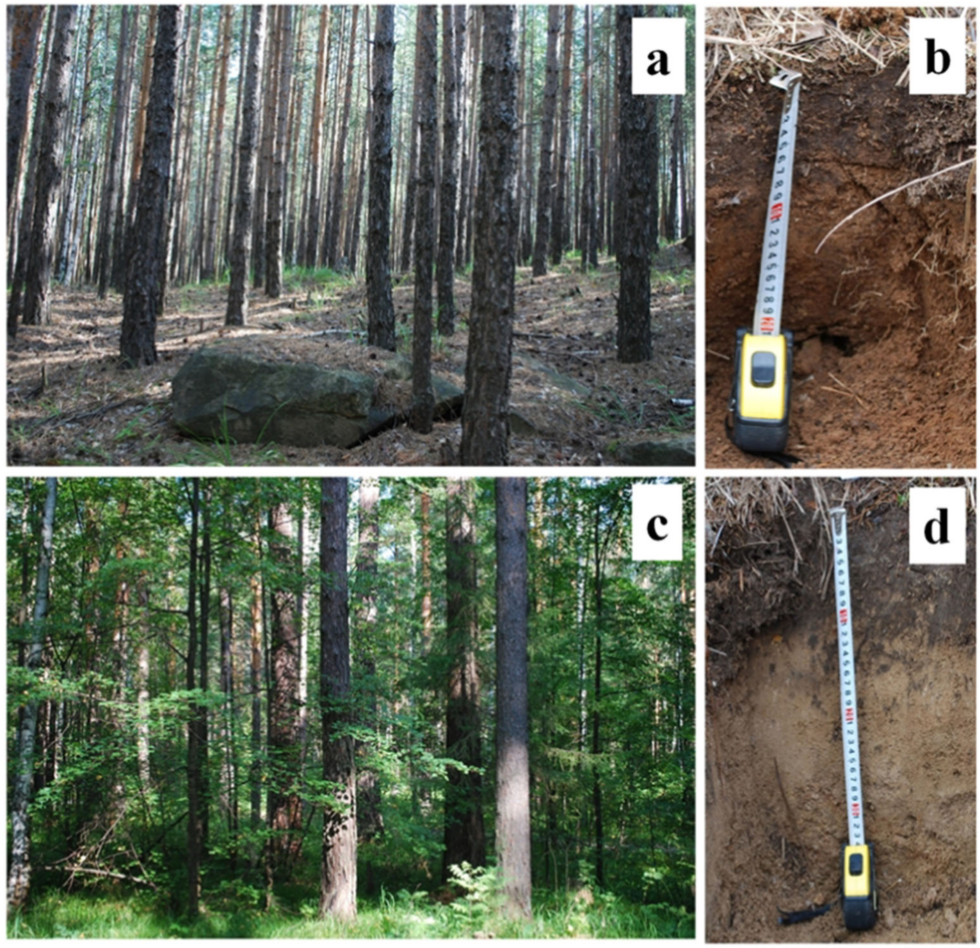

Fig. 2 The investigated forest types and soil: **a**, **b** the cowberry shrub pine forests and brown forest soils under their canopy; **c**, **d** the berry pine forests with linden and brown forest soils under their canopy

leaved grassy mesophytic forests of the Central and Western Ural forests), and alliance Trollio europaea-Pinion sylvestris (mesophytic pine-birch grass forests on fertile and well-moistened soils). This class is characterized by a closed, well-developed forbs and grass-shrub layer and increased species richness (Ivanova and Zolotova 2013).

Materials and methods

The sample plots were established in two forest types of Trans-Ural hilly-foothill province, cowberry-pine forests and berry pine forests with linden, and their corresponding clear-cuttings to study the transformation of the copper smelting slag recycling waste of the Sredneuralskiy smelter in natural ecosystems.

The copper smelting slag recycling waste of the Sredneuralskiy smelter ("SUMZ") is a finely dispersed material called "technical sand," which contains about 3.4% zinc, 0.4% copper, 0.4% lead, and 35.0% iron (Kotelnikova and Ryabinin 2018). The granulometric composition of the "sands" is as follows: size of slag particles 0.21–0.10 mm, 1.1-4.1%; 0.1–0.05 mm, 21–30%; and < 0.05 mm, 69–75% (Reutov et al. 2015). The copper smelting slag recycling waste of the "SUMZ" has a pH = 4 at the beginning of the water leaching process and pH = 5–6 at the end of this process (Kotelnikova 2008). The chemical composition of the copper smelting slag recycling waste is given in Table 1.

"Technical sand" was introduced into the brown forest soils of the selected forest ecosystems in the autumn (September–October) before the snow cover was established. The field experiment to assess the element mobility from the copper smelting slag recycling waste into soil and their effect on forest vegetation was done in two variants. The task of the first variant of the field experiment was to evaluate the effect of "technical sand" on the diagnostic and dominant species of grass-shrub layer of selected native forests and their corresponding clear-cutting sites. We laid 4 sites (1 × 1 m^2) on each sample plots for two forest type and two corresponding clear-cuttings. As a result, we got sixteen experiment plots. On them, we evenly scattered 1 kg of the copper smelting slag recycling waste. In the following summer, we estimated the species composition of the sample plots using field geobotany methods (Okland and Eilertsen 1994) and ecological-floral classification (Braun-Blanquet 1964). The assessment was

Table 1 The chemical composition (elements and compounds) of the copper smelting slag recycling waste of the Sredneuralskiy smelter (“technical sand of SUMZ”)

Compounds	Mass fraction, %			Compounds/ elements	Mass fraction, %		
	1	2	3		1	2	3
SiO_2	31.0	32.7	35.8	H_2O	–	0.18	–
Al_2O_3	7.05	5.15	7.78	Cu	0.44	–	0.34
Fe_2O_3	14.3	11.1	10.1	Zn	3.28	3.94	2.93
FeO	32.3	36.8	35.8	Pb	0.20	–	0.08
TiO_2	0.26	0.20	0.26	S	1.32	0.81	2.75
MnO	0.09	0.09	–	As	0.53	–	0.01
CaO	4.53	3.63	0.97	Ba	0.43	–	–
MgO	1.64	1.57	1.09	Ni	0.001	–	–
K_2O	0.74	0.72	0.82	V	0.004	–	–
Na_2O	0.64	0.62	0.83	Mo	0.02	–	–
P_2O_5	0.18	0.16	0.62				

The analyses done at the analytical center “Geoanalitik” of the Institute of Geology and Geochemistry, Ural Branch of Russian Academy of Sciences (RAS) (1), at the Institute of Mineralogy Urals Branch of RAS (2) (Kotelnikova and Ryabinin 2018), and at the Ural State Mining University (3) (Guman et al. 2010). Dash, no data.

carried out during the period of maximum development of herb layer in July. The flowchart of the experiment is shown in the Figure 3.

The task of the second variant of the field experiment was to evaluate the element mobility from the copper smelting slag recycling waste into brown forest soils under the forest canopy and in clear-cutting site (Fig. 3). We weighed 100 g of “technical sand,” packed it into non-woven material, and buried in the soil profile of the sample plots to a depth of 7–10 cm into the humus horizon (A1). The experiments were carried out in triple repetition. The experiment was done as accurately as possible, trying to inflict minimal damage. The forest litter was removed during the introduction of the waste and then returned to the place. We conducted this experiment in the autumn period (similar to the first variant). Twelve bags of industrial waste were laid in the humus horizon of soils of two forest types of pine and clear-cuttings. We dug out bags of waste

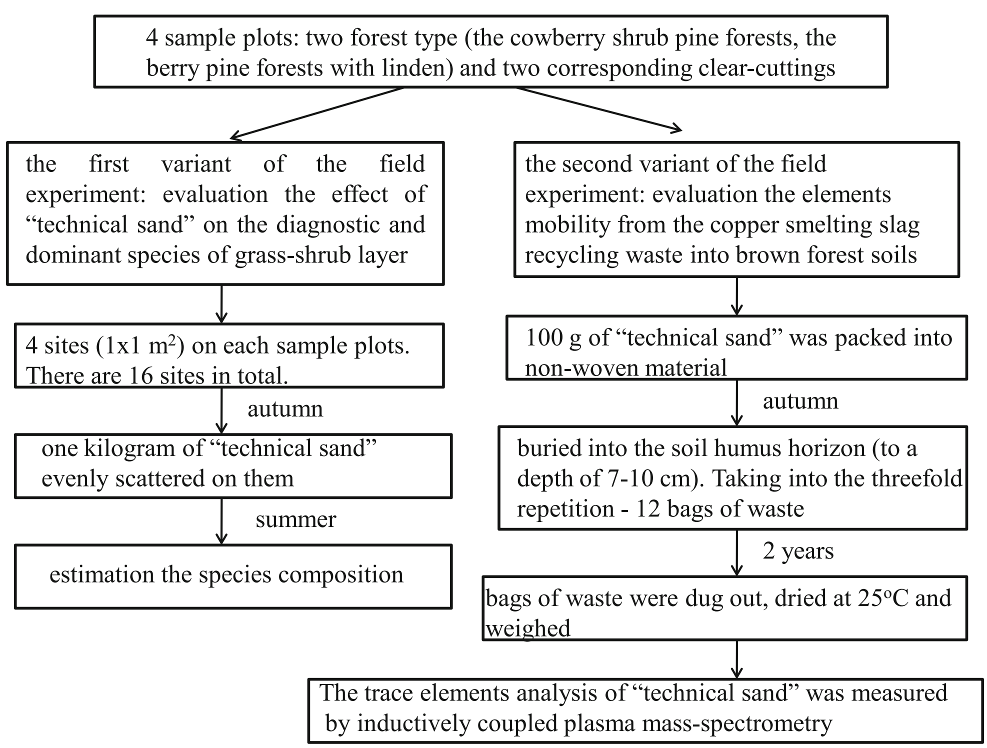

Fig. 3 The flowchart of the experiment to assess the impact of copper smelting slag recycling waste of the Sredneuralskiy smelter (“technical sand”) on forest ecosystems in the Middle Urals (Russia)

after 2 years, dried at 25 °C to constant weight, weighed, and determined the chemical composition.

The trace element analysis of the copper smelting slag recycling waste of the Sredneuralskiy smelter was carried out at the analytical center "Geoanalitik" of the Institute of Geology and Geochemistry, Ural Branch of RAS. The trace element composition of the "technical sand" before and after the experiment was measured by inductively coupled plasma mass spectrometry using Elan-9000 ICP mass spectrometer. The sample preparation was performed by acid decomposition, followed by autoclave mineralization in the microwave oven "Gefest." The obtained element concentrations agree with available reference values to a tolerance of about 15%. Statistical analysis of the data is based on the one-way ANOVA.

Results

The first variant of the field experiment on introducing the copper smelting slag recycling waste into the brown forest soils (Haplic Cambisols) of the Middle Urals made it possible to evaluate the effect of "technical sand" on the diagnostic and dominant types of grass-shrub layer of two forest types, the cowberry-pine forests and the berry pine forests with linden, and their corresponding clear-cuttings site. It was found that a single surface application in the autumn period of 1 kg/m^2 of the copper smelting slag recycling waste did not affect the qualitative composition of the grassy layer of all investigated forest types and corresponding clear-cuttings in the next spring–summer period. Diagnostic and dominant species of the grass-shrub layer of the investigated forest types did not change when this concentration of "technical sand" was introduced (Table 2).

In the second variant of the field experiment, we introduced the 100 g of "technical sand of SUMZ" into the humus horizon of the brown forest soils of two forest types and the corresponding clear-cuttings, in order to evaluate the element mobility from mineral waste. We found that in 2 years, about 11 g of waste were mobilized (the waste initial weight equal to 100 g). The relationship between the two types of forests (two moistening modes: periodically dry and steadily fresh) and the succession status (deforestation) was not established (Table 3).

The content of the most chalcophilic elements of the copper smelting slag recycling waste decreases after a 2-year stay in the humus horizon of brown forest soils (Haplic Cambisols). Statistically significant differences were found for 11 chalcophilic elements out of 13 studied (Table 4). The content of Zn, As, Cd, and Se changes most strongly. When comparing two indigenous forest types, it was found that the greatest element mobility from the "technical sand of SUMZ" was revealed in the soil humus horizon (light loam, pH_{H2O} = 5.10, pH_{KCl} = 4.06) under the canopy of the berry pine forests with linden. However, arsenic migrates much more strongly to the upper horizon of soil under the canopy of cowberry shrub pine forest (sandy loam, pH_{H2O} = 5.24, pH_{KCl} = 3.95). When comparing the forest types and the corresponding cuttings, it was found that the migration of chalcophilic elements is slightly stronger in the humus horizon of the clear-cutting soils. The tendency revealed for forest soils persists: the processes of migration from mineral industry waste to brown forest soil of the clear-cutting of the berry pine forests with linden mainly occur more intensively than to soil of the clear-cutting of the cowberry shrub pine forest (Table 4).

Discussion

The recycling of cast copper smelting slag involves grinding the cast slag, followed by flotation recovery of the copper concentrate. The specific surface area of grains, permeability to water, and atmospheric gases increase many times as a result of grinding cast slag. The mechanical activation processes of the material occur, and its enthalpy increases. Thus, the "technical sand" (slag particles < 0.05 mm) has different properties than the original cast copper smelting slag, and we assume that it will interact more strongly with

Table 2 Diagnostic and dominant species of grass-shrub layer of two pine forest types and corresponding clear-cuttings of the Trans-Ural hilly foothill province

Forest ecosystems	Diagnostic species	Dominant/predominant species
The cowberry shrub pine forest	*Vaccinium vitis-idaea*, *Antennaria dioica*	*Calamagrostis arundinacea*, *V. vitis-idaea*
The clear-cutting of the cowberry shrub pine forest		*C. arundinacea*, *V. vitis-idaea*, *V. myrtillus*, *Rubus saxatilis*
The berry pine forests with linden	*Vaccinium myrtillus*, *Rubus saxatilis*, *Carex digitata*	*V. myrtillus*, *V. vitis-idaea*, *C. arundinacea*
The clear-cutting of the berry pine forests with linden		*C. arundinacea*, *Chamerion angustifolium*, *Brachypodium pinnatum*

Table 3 The copper smelting slag recycling waste mass loss after 2 years of being in the humus horizon of brown forest soils of the Trans-Ural hilly foothill province

Forest ecosystems	Mass loss of "technical sand of SUMZ" (mean), g	Standard deviation
The cowberry shrub pine forest	11.1	0.759
The clear-cutting of the cowberry shrub pine forest	11.0	0.477
The berry pine forests with linden	11.3	1.56
The clear-cutting of the berry pine forests with linden	11.0	0.651

environmental objects. This is confirmed by the research of potential environmental risks due to mechanical disturbances slag deposits (Tyszka et al. 2014). Although in this study, the slag particles are up to 5 cm in size.

The element mobility from the copper smelting slag recycling waste depends on its mineral composition. Therefore, we turned to earlier studies of microscopic mineral fragments that compose these waste products. Detailed studies of the "technical sand of SUMZ" were carried out on a JSM-6390LV scanning electron microscope with an INCA Energy 450 X-Max 80 energy-dispersive attachment (Kotelnikova and Ryabinin 2018). The authors revealed the following series of mineral phases in decreasing order: fayalite, ferruginous glass, willemite, pyroxenes, magnetite, hematite, wustite, quartz, pyrrhotite, pyrite, cuprite, as well as matte and speiss. According to the phase composition, "technical sand" mainly consists of fayalite (Fe_2SiO_4), 45%; ferruginous glass, 30%; diopside (CaZn (Si_2O_6)), 8%; and magnetite (Fe_3O_4), 3.5%. It was found that heavy and non-ferrous metals, including copper, are mainly concentrated in matte and speiss in the form of sulfides and intermetallides. Zn is observed in all phases: about 43% in matte in the form of sulfides and more than 50% in the form of isomorphic impurities in fayalite and glass. The bulk of alkaline and alkaline earth elements, Al, and silicon are in the glass phase. About 50% of the iron is enclosed in a fayalite (Kotelnikova and Ryabinin 2018).

It was interesting to consider the results of laboratory experiments to study water migration (Guman et al. 2010; Kotelnikova 2008), as well as modeling the effects of soils and acid precipitation on "technical sand" (Kotelnikova 2010, 2012). Scientists conducted research using distilled water and melt snow water, which characterizes the composition of atmospheric precipitation in the area adjacent to the storage areas of "technical sand" (Guman et al. 2010). It was established that in aqueous solutions, there is a very strong migration activity for S, Na, and Ca; strong, for Mg, K, P, and

Table 4 The changes in chalcophilic element content of "technical sand" after a 2-year stay in the humus horizon of brown forest soils of two forest types and clear-cuttings in the Trans-Ural hilly foothill province

	The chemical element content in the copper smelting slag recycling waste, mg/kg					*F* value (4.12)	Sig. Level (p)
Element	Initial	Cowberry shrub pine forest	Clear-cutting of the cowberry shrub pine forest	Berry pine forests with linden	Clear-cutting of the berry pine forests with linden		
Cu	1.667	1.218	1.163	1.039	1.093	19.893	0.00003*
Zn	12.145	4.969	4.737	4.314	4.471	297.09	0.00000*
Ga	8.58	5.47	5.19	4.65	4.72	80.152	0.00000*
As	421	195	192	230	222	25.012	0.00001*
Se	2.67	1.14	1.13	1.03	1.07	49.141	0.00000*
Ag	0.87	0.727	0.704	0.664	0.669	7.9533	0.00226*
Cd	3.57	0.16	0.268	0.103	0.162	781.68	0.00000*
Sn	19.5	15.8	15.8	14.6	14.9	13.388	0.00022*
Sb	142	141	140	130	134	1.4093	0.289
Te	0.161	0.16	0.157	0.137	0.14	1.3255	0.3159
Tl	0.537	0.385	0.383	0.355	0.367	41.064	0.00000*
Pb	1.020	783	782	732	757	24.11	0.00001*
Bi	1.01	0.811	0.8	0.764	0.772	13.894	0.00019*

*Statistically significant $p < 0.05$ was observed, and the critical value of the Fisher test is given in brackets. If the actual value of F is greater than or equal to the critical (standard) value of F, the differences between the samples are statistically significant

Mn; and the average, for Zn and Pb. Migration activity of Cu varies from medium to weak depending on the slag/water ratio (Kotelnikova 2008). In the experiment of modeling the soil, waste system was performed using a 1 M acetate-ammonium buffer solution. As a result, a series of migration activity of the elements was compiled (from maximum to minimum): Mg > Mn > Na > P > Fe > Zn > Ca > Pb > As > S > Si > Al > Cu. The author concluded that technical sand will be easily decomposed by soil solutions containing a large number of organic compounds, with the transition of iron, manganese, and heavy metals into a solution in the form of organometallic complexes and the formation of finely dispersed fayalite, clay phase (Kotelnikova 2010).

The first field experiments to study the interaction of soils and the copper smelting slag recycling waste were carried out in 2003–2005 (Leontiev and Ryabinin 2005, 2007). The researchers introduced "technical sand" into the humus-accumulative horizon A1 (A1A2) of two soils types: sod-podzolic and gray forest soils (Shali district of the Sverdlovsk region, subzone of the southern taiga). The experiment was carried out by the following method. They removed the top layer of sod, evenly introduced slag at a concentration of 1 kg/m^2 into the humus-accumulative horizon to a depth of 15–20 cm, and mixed with the soil mass, after which the exposed layer of soil was covered with removed sod. An increase in the gross concentrations of copper and zinc and a decrease in the silver content in the upper soil horizon were revealed by the results of the first year. Scientists have hypothesized that this process is little affected by differences in soil types (Leontiev and Ryabinin 2005). We do not agree with this statement. As a result of our research, it was shown that changes in soil properties, as well as plant communities growing on these soils, lead to changes in the element mobility from "technical sand." The geochemical situation in the studied soils changes 2 years after the start of the experiment. The content of Cd, Cu, Zn, and Pb in the humus-accumulative horizon of sod-mid-podzolic soil increases (more than twice) a year after the introduction of slag and decreases the next year. Silver content continues to decline in the second year of the experiment (Leontiev and Ryabinin 2007).

Comparison of our data on the element mobility from "technical sand" to brown forest soils with the results of colleagues (Leontiev and Ryabinin 2005, 2007) on sod-podzolic and gray forest soils is difficult due to differences in methods. However, the general patterns that were revealed are similar. According to our data, the copper smelting slag recycling waste of SUMZ loses up to 11% of the mass for 2 years in forest soils, which is due to exposure under the influence of the natural factors complex (seasonal temperature fluctuations, humidity, soil composition and properties, the effect of vegetation and lithophilic microorganisms). The highest migration activity of chalcophilic elements was found for Cd, Zn, Se, and As. Other authors (Kotelnikova 2012) also indicate that the multifactorial effect of environmental conditions on the copper smelting slag recycling waste leads to a change in the ratio of water-soluble, mobile, and potentially mobile forms of heavy metals. The long-term presence of slag in the soil solutions significantly increases the content of water-soluble (ionic) forms of heavy metals (Kotelnikova 2012).

Thus, our research results are consistent with literature data and supplement them with new knowledge about the element mobility from the "technical sand of SUMZ" in the soil of natural ecosystems. However, many issues remained. We think that additional research is needed to concretize the measures for each of these natural (environmental) factors to participate in the chemical element mobilization from the mineral waste.

Conclusion

An assessment of the element mobility from the waste of the copper smelting slag recycling waste of the Sredneuralskiy smelter into brown forest soils (Haplic Cambisols) under the canopy of two forest types (the cowberry shrub pine forest, the berry pine forests with linden) and on the corresponding clear-cuttings was carried out.

We found that the technical sand of "SUMZ" for 2 years of being in the humus horizon of brown forest soils lose about 11% of the mass. The content of zinc, arsenic, cadmium, and selenium changes most strongly. The difference in the degree of element migration from the "technical sand" to the brown forest soils of the two forest types and the corresponding clear-cuttings was revealed.

We made the first attempt to investigate the effect of technogenic waste on the dominant and diagnostic species of the grass-shrub layer of two pine forest types and the corresponding clear-cuttings of the Middle Urals. The negative effect on the grassy vegetation of the selected ecosystems was not revealed after a single surface application of waste in a concentration of 1 kg/m^2. However, further research is needed. Data on the projective cover and biomass of the grass-shrub layer, as well as long-term studies, will allow more accurately and justifiably to draw a conclusion about the ongoing changes in forest ecosystems under the influence of "technical sand."

The existing scientific backlogs on studying the waste of the copper smelting slag recycling waste of the Sredneuralskiy smelter and the initial results of field experiments allow us to conclude that the introduction of "technical sand" in forest ecosystems, as part of its disposal, is possible. However, further studies are needed to analyze the distribution of elements migrating from waste along the soil profile of forest soils and their involvement in biogeochemical cycles and to study the accumulation of elements by plants.

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Data availability All data generated or analyzed during this study are included in this published article.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethics approval and consent to participate Not applicable.

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