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Chemical and ecological properties of soils and the NDVI analysis on reclaimed sulfide coal waste dumps in the boreal zone

N.V. Mitrakova, E.A. Khayrulina, A.A. Perevoshchikova, N.V. Poroshina, E.E. Malyshkina, E.S. Yakovleva, N.A. Kobelev

Institute of Natural Science of Perm State National Research University, Perm, Russian Federation

✉ *mitrakovanatalya@mail.ru*

Abstract

Reclamation of coal waste dumps through the establishment of a stable soil and vegetation cover on their surface contributes to the restoration of ecological systems. Therefore, studying the properties of soils in technogenic landscapes is of current importance. The problem of biological reclamation was studied in the Kizel Coal Basin area. The effectiveness of reclamation was evaluated on several sulfide coal waste dumps. The reclamation methods, as well as the period of soil-vegetation cover formation, varied. Agrochemical properties of the dump soils were studied using unified methods. The NDVI (Normalized Difference Vegetation Index) was calculated based on Sentinel-2 and Landsat 7,8 images. To assess biological activity, phytotesting was used. The lithostrats ranged from slightly acidic to neutral (pH–H_2O = 6.1–6.8); the embryonic soil showed a slightly alkaline reaction (7.9). The embryonic soil, due to the presence of coal particles, had the highest organic matter content (12–7.7%). Depending on the "age" of the soil, the amount of organic matter in the lithostrats varied: for the 7-year-old lithostrat, it ranged from 2.4 to 8.9%, while for the 4-year-old lithostrat, it was less than 1%. The absorption capacity of the lithostrats was similar to that of the background soil. The dump soils were characterized by low levels of nutrients (NPK), with the 4-year-old lithostrat having the lowest N content. The dump soils demonstrated favorable conditions for plant growth, as evidenced by the height and biomass of cress and oats. The calculated NDVI for all dumps ranged from 0.4 to 0.6, indicating the presence of a stable vegetation cover. The implemented reclamation measures proved to be effective.

Keywords

coal, dump, waste, reclamation, soil formation, lithostrat, soil, NDVI index, embryonic soil, Fe^{2+}, SO_4^{2-}, H^+, pH

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ТЕХНОЛОГИЧЕСКАЯ БЕЗОПАСНОСТЬ В МИНЕРАЛЬНО-СЫРЬЕВОМ КОМПЛЕКСЕ И ОХРАНА ОКРУЖАЮЩЕЙ СРЕДЫ

Научная статья

Химико-экологические свойства почв и индекс NDVI на рекультивированных сернистоугольных отвалах бореальной зоны

Н.В. Митракова, Е.А. Хайрулина, А.А. Перевощикова, Н.В. Порошина, Е.Е. Малышкина, Е.С. Яковлева, Н.А. Кобелев

Пермский государственный национальный исследовательский университет, г. Пермь, Российская Федерация

✉ *mitrakovanatalya@mail.ru*

Аннотация

Рекультивация угольных отвалов путем создания устойчивого почвенного и растительного покрова на их поверхности способствует восстановлению экологических систем. В связи с этим актуальным является изучение свойств почв техногенных ландшафтов. Проблема биологической рекультивации изучалась на территории Кизеловского угольного бассейна. Оценена эффективность рекультивации на нескольких сернистоугольных отвалах. Методы рекультивации, как и период формирования почвенно-растительного покрова, различались. Агрохимические свойства почв отвалов изучали стандартными методами. Индекс NDVI (нормализованный относительный индекс растительности) рассчитан по снимкам Sentinel-2 и Landsat 7,8. Для оценки биологической активности использовали фитотестирование. Литостраты варьировались от слабокислых до нейтральных (pH–H_2O = 6,1–6,8); эмбриозем имел слабощелочную реакцию (7,9). Эмбриозем благодаря наличию частиц угля имел наибольшее содержание органического вещества (12–7,7 %). В зависимости от «возраста» почвы количество органического вещества в литостратах варьировало: для 7-летнего литострата оно колебалось от 2,4 до 8,9 %, а для 4-летнего было меньше 1 %. Поглотительная способность литостратов была аналогична с фоновой почвой. Почвы отвалов характеризовались низким уровнем питательных элементов (NPK), а 4-летний литострат имел самое низкое содержание N. Почвы отвалов показали благоприятные условия для роста растений, о чем свидетельствуют высота и масса кресс-салата и овса. Рассчитанный индекс NDVI для всех отвалов имел значения от 0,4 до 0,6, что свидетельствует о наличии устойчивого растительного покрова. Реализованные рекультивационные мероприятия доказали свою эффективность.

Ключевые слова

уголь, отвалы, отходы, рекультивация, почвообразование, литострат, почва, индекс NDVI, эмбриозем, Fe^{2+}, SO_4^{2-}, H^+, pH

Финансирование

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Introduction

The mining industry, particularly coal extraction, significantly contributes to the transformation of natural ecosystems. Underground mining causes changes in the landscape and surface subsidence. For instance, in a study [1], subsidence was determined based on the growth rings of European larch (*Larix decidua*), where the authors confirmed the highest subsidence activity during periods of intensive mineral extraction. As a result of mining operations, land is reclaimed for waste disposal. In the Kuznetsk Coal Basin alone, approximately 3.6 billion tons of waste are generated annually, and the area of land disturbed by open-pit mining has now increased to 16.4 hectares per million tons of extracted coal [2]. Soils adjacent to waste dumps exhibit high concentrations of polycyclic aromatic hydrocarbons (PAHs) [3], the sources of which are emissions from burning dumps. These emissions spread to nearby areas via atmospheric transport. Naphthalene has been detected in the emissions from burning dumps, with higher concentrations found in waste containing pyrogenic bitumen. Additionally, anthracene, phenanthrene, fluoranthene, and pyrene were identified, with the last three indicating intense oxidation of organic matter [4]. Soils in coal mining areas are frequently contaminated with heavy metals. In one study [5], elevated concentrations of Cr, Ni, and Hg were found in the soils of mining regions compared to regulatory standards. The presence of trace elements in coal contributes to soil and water contamination. For example, the authors of [6] found that during leaching, coal-bearing rocks release Se, Cd, Hg, As, Be, V, Cr, and Pb. High concentrations of Fe, Al, Mn, Be, and other elements in the rivers of the Kizel Coal Basin have been described in studies [7, 8]. The use of the *Igeo* coefficient revealed contamination by Co, V, Nb, Hg, Sn, Zn, Sm, Ni, Cr, and Gd in the bottom sediments of the Kosva River in the Kizel Coal Basin area [9]. In addition to environmental pollution, coal mining leads to changes in the hydrological regime. Research results [10] showed that runoff, runoff depth, and spring runoff decreased by approximately 25%, 30%, and 57%, respectively, as a result of coal mining, while the calculated soil erosion rates and soil loss increased by nearly 200%.

The coals and coal-containing rocks in large-scale mining waste dumps contain significant amounts of sulfides and organic sulfur as part of the mineral composition of the dumps, with the sulfur content in coals varying across different deposits. In the coals of the Kizel Coal Basin, sulfur content ranges from 5 to 8%, with sulfur primarily present in the form of pyrite [11]. A study by Singh and Narzary [12] on overburden and coal seams at the Tikok mine in India showed that sulfur content in different seams ranged from 0.02% to 2.5%, with the maximum sulfur content in the coal seam reaching 1.9%.

Pyrite and other sulfides in overburden dumps are chemically unstable under oxidizing conditions. Initially, when exposed to water and oxygen at a neutral pH, pyrite undergoes chemical oxidation, releasing Fe^{2+}, SO_4^{2-}, and H^+ [13]. In the presence of O_2, ferrous iron (Fe^{2+}) is oxidized to ferric iron (Fe^{3+}), leading to increased acidity in the water and enhanced activity of Fe^{3+} ions. Acidophilic microorganisms accelerate pyrite oxidation, resulting in the formation of acidic mine drainage [13]. These acidic waters, with a pH of 2.5–3, are saturated with heavy metals, trace elements, and sulfates [14], making coal waste dumps sources of environmental pollution.

Natural revegetation on coal dumps occurs slowly due to the high acidity caused by the oxidation of sulfide minerals in overburden rocks, nutrient deficiencies, and the unfavorable mechanical composition of the substrate. Reclamation significantly reduces the time required for soil and vegetation cover to form on dumps. Reclamation efforts on coal dumps raise soil pH values from ultra-acidic (pH-H_2O 2.7) to neutral levels (pH-H_2O 6.4) [15]. Changes in acidity promote vegetation recovery, improving soil quality by increasing the organic matter and nutrient (NPK) content. According to [16–18], both plant community density and biodiversity increased in older reclaimed areas.

Soil formation on coal mining waste dumps helps prevent the spread of contaminants into the environment [19, 20]. Reclamation of dumps and disturbed lands, along with vegetation and soil restoration, are essential for preserving the natural environment and preventing the negative consequences of resource extraction [21, 22].

The Kizel Coal Basin (KCB) is located in the eastern part of the Perm region (Fig. 1) and covers an area of approximately 1,500 km^2 [7]. Extensive surveys of surface waters and bottom sediments have been conducted in the KCB area [7, 8, 23]. However, the current condition of the soils on KCB dumps has not been sufficiently studied. While some coal dumps in the KCB have undergone reclamation, there have been no large-scale scientific studies. After the closure of the mines, there were attempts to study the soils formed on the dumps [24, 25], but these were isolated studies and did not include diagnostics, classification, or detailed chemical analyses.

The aim of this work is to study the chemical and ecological properties of anthropogenic soils formed as a result of coal dump reclamation, to classify the formed soils, and to assess the effectiveness of reclamation using the NDVI index and phytotesting.

Materials and Methods

Description of the study area

The study area is part of the Ural Geochemical Province, within the eluvial-transalluvial region of residual mountain ranges on the western slope of the Middle Urals. According to the landscape zoning, the study area belongs to the the VerkhneYaivinskiy high ridge-hummocky landscape which lies on Paleozoic carbonate and partially terrigenous rocks. The climate is moderately continental, with an average annual precipitation of 700 mm. In the system of modern soil-ecological zoning, the Kizel Coal Basin (KCB) area is classified within the Western Foothill District, characterized by heavy loam podzolic, sod-podzolic, and waterlogged soils. The region of the study is situated in the mid- and southern-taiga zones, dominated by fir-spruce and spruce-fir forests in the foothills.

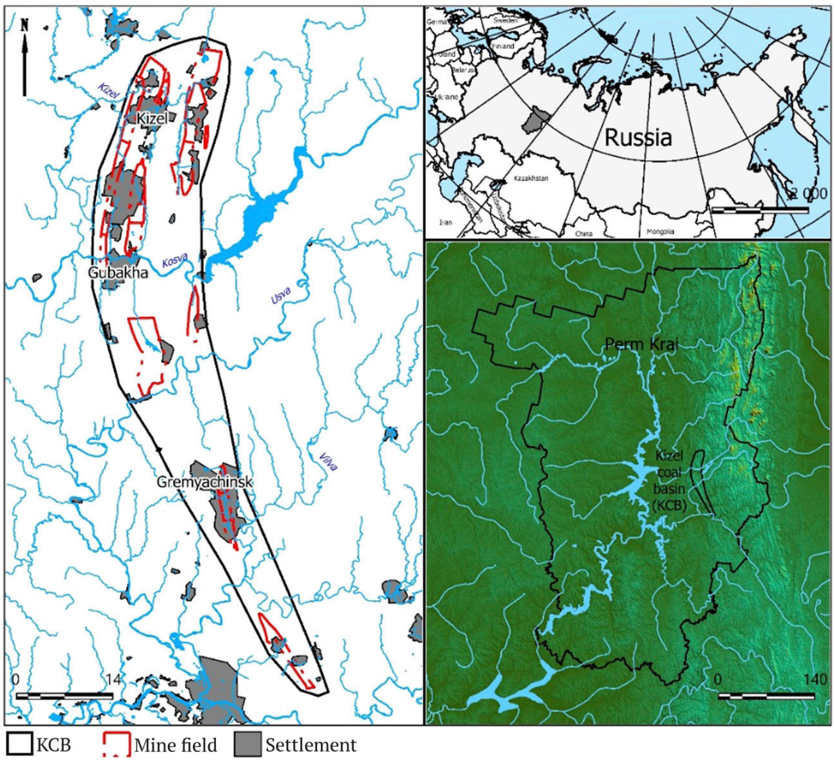

Fig. 1. Geographic location of the Kizel Coal Basin

Underground coal mining in this region took place from the late 18th century until the end of the 20th century, with the mines being closed in the early 2000s. There are approximately 100 spoil heaps in the KCB area [7]. According to satellite images from 2021, the area covered by these dumps reached 260 hectares. Over the course of mining operations, more than 35 million m^3 of rock waste accumulated. The lithology of the coal-bearing strata, mining technology, spoil heap storage methods, and the age of the heaps have all contributed to the heterogeneity of the dump material, which contains around 60 minerals [7]. The heaps consist of argillites, siltstones, sandstones, limestones, coal, pyrite, as well as wood and metal objects [26].

Soil sampling

In the summer of 2021 and 2022, soil samples were collected from three reclaimed waste dumps (Fig. 2) at a depth of 30 cm. The presence of a large amount of stony material made it difficult to collect samples from deeper layers. The soil samples were taken from the central part of the waste dumps, where the surface had been leveled prior to reclamation. In a 5×5 meter area, three pits were dug, and samples were collected from depths of 0–10 cm, 10–20 cm, and 20–30 cm. Before sampling, the vegetation at each collection site was cleared. The soil samples were extracted using a stainless steel trowel. Samples from each dump and corresponding depths were combined. The combined samples were then packed into polyethylene bags labeled with sample codes, dates, and collection locations. Each composite sample weighed at least 1 kg. As background samples, sod-podzolic soils were collected from a mixed forest.

Pit 1 was established on the waste dump of the Severnaya Mine in Shakhta settlement (Fig. 2(1)) (59°4’58.62”N 57°40’59.29”E). This dump was reclaimed in the early 2000s by leveling and adding slaked lime to the upper layer. Currently, the dump has a flat surface.

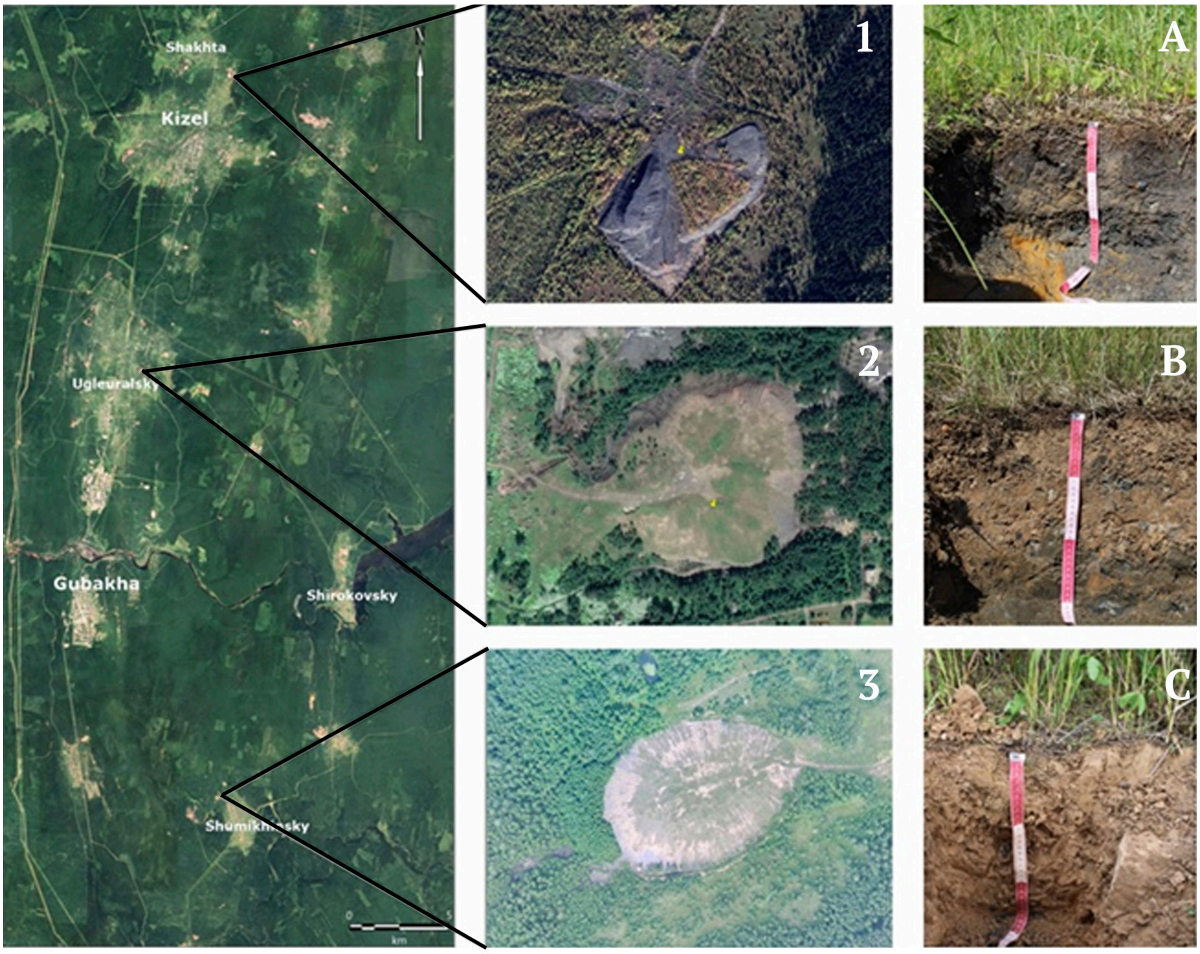

Fig. 2. Soil sampling locations and soil profiles:
1 – Severnaya Mine waste dump; *A* – soddy embryonic soil; *2* – Tsentralnaya Mine waste dump; *B* – clay lithostrat No. 1; *3* – Gorelovskaya Mine waste dump; *C* – clay lithostrat No. 2

Pit 2 was established on the waste dump of the Tsentralnaya Mine in Ugleuralsky settlement (Fig. 2(2)) (58°56'54.31"N 57°36'15.50"E). In 2016, the dump was reclaimed by leveling and covering it with a 0.3–0.5 m layer of clayey material. Sporadic mounds of construction debris are observed on the dump.

Pit 3 was established on the waste dump of the Gorelovskaya Mine in Shumikhinsky settlement (Fig. 2(3)) (58°45'21.25"N 57°40'17.25"E). In 2018, the dump was reclaimed by leveling and covering it with a layer of clayey material about 0.3 m thick.

Sod-podzolic soil samples from a secondary small-leaved forest were collected as background samples.

Research methods

Actual and exchangeable acidity in the soil samples was determined using the potentiometric method. Hydrolytic acidity was measured using the Kappen method (in a 1M CH_3COONa solution), which involves titration with a 1N alkali in the presence of phenolphthalein. Exchangeable acidity, exchangeable aluminum, and exchangeable hydrogen were determined by the Sokolov method, which is based on treating the soil with a 1M KCl solution, followed by titration. One part of the extract was titrated with alkali to determine the sum of exchangeable aluminum and hydrogen, while another part of the extract was titrated with alkali and fluoride to identify hydrogen ions. Acidity in hydrogen peroxide was determined to oxidize sulfide minerals present in the dumps; a pH lower than 2.5 in the peroxide solution indicates the presence of sulfide minerals.

The organic matter content was determined by the spectrophotometric method in accordance with GOST 26213–91. The cation exchange capacity (CEC) was determined using the Bobko-Askinazi-Aleshina method (GOST 17.4.4.01–84). The contents of exchangeable calcium and exchangeable (mobile) magnesium were measured using complexometric titration according to GOST 26487–85. The mobile sulfur content was determined by the turbidimetric method (GOST 26490–85), and mobile iron by the spectrophotometric method with o-phenanthroline according to GOST 27395–87. Sulfate ions were measured by the turbidimetric method (GOST 26426–85). Mobile phosphates and potassium were determined by the Kirsanov method, based on the extraction of mobile phosphates and potassium from the soil using a 0.2M HCl solution. Mobile phosphates were then measured as blue phosphorus-molybdenum complexes using a photoelectric colorimeter, while mobile potassium was determined using a flame photometer. The content of mobile potassium and phosphates in the dump soils was evaluated according to the criteria [27].

The biological activity of the soils was studied based on a patented method[1]. Phytotesting of the upper soil layers (0–10 cm) from the reclaimed waste dumps was conducted using cress (*Lepidium sativum*) and oats (*Avena sativa*). Cress was grown on both the waste dump soils and background soils for 7 days, and oats for 10 days. The height and biomass of the plants were measured in 25 replicates. A 10–30% reduction in cress growth indicates satisfactory soil conditions, while a reduction of 30–50% indicates unsatisfactory conditions. A reduction of more than 50% suggests environmentally hazardous soil conditions. As a control, plants were grown on vermiculite with Knop nutrient solution (1 g/l $Ca(NO_3)_2$, 0.25 g/l KH_2PO_4, 0.25 g/l $MgSO_4$, 0.125 g/l KCl, 0.0125 g/l $FeCl_3$).

To calculate the NDVI index for the dump areas, Sentinel-2 images (for lithostrat 2) and Landsat 7,8 images (for the embryonic soil and lithostrat 1) were used from the years 2000, 2007, 2014, 2018, 2020, and 2023. The necessary satellite images and spectral channels were obtained using the EOS LandViewer service.

The NDVI (Normalized Difference Vegetation Index) is an indicator of active biomass and is calculated as the ratio of the difference between the near-infrared and red spectral bands to their sum. NDVI values range from −1 to 1 and allow for the assessment of vegetation development during the growing season. Negative values of the index typically correspond to water bodies, clouds, or built-up areas. Low positive values (from 0 to 0.3) indicate either a complete absence of vegetation (approximately from 0 to 0.1) or sparse shrub or grass vegetation (up to 0.3). Values in the range of 0.3 to 0.5 correspond to moderate vegetation, while values between 0.5 and 1 indicate dense vegetation, often represented by forested areas.

Monitoring the dynamics of the NDVI index on reclaimed waste dump sites allows for an assessment of the success of reclamation efforts.

The NDVI was calculated using the Raster Calculator tool from the Spatial Analyst toolbox in ArcMap 10.4. To enhance the visual representation of the obtained rasters, the cubic convolution resampling method was applied.

Statistical parameters, such as the mean value and coefficient of variation (CV), were calculated using STATISTICA 7 and Microsoft Excel. For statistical processing of the data, regression and correlation analyses were conducted with a confidence level of 95%. Soil samples were compared based on agrochemical parameters using the non-parametric Kruskal-Wallis test. Significant differences between the compared

[1] Yeremchenko, O.Z., Mitrakova, N.V. Method for assessing the biological activity and toxicity of soils and technogenic soil substrates: RF patent. 2017. Bulletin No. 15. No. 2620555.

mean values were considered at a confidence level of 95% or higher ($P < 0.05$). The significance of differences between plant height and biomass was assessed using the Student's t-test ($P < 0.05$).

Results

Soil classification and vegetation changes

The background soils of the study area are zonal sod-podzolic loamy soils. Due to the exploitation of waste dumps, the natural soil cover has been altered. Overall, the soil cover of the dumps is heterogeneous, and technogenic soils or technogenic surface formations (TSF) have developed on the dumps.

The soddy embryonic soil was identified on the Severnaya Mine dump according to the classification proposed by [28]. According to the World Reference Base for Soil Resources (WRB), this soil can be classified as Epileptic Technosol (Densic, Carbonic, Skeletic) (Fig. 2, A). The surface soil has a dark gray color, with a sod layer of 2 cm thickness characterized by a cloddy structure. Beneath this layer is a dense material mixed with stones of various sizes, with fine earth observed in the upper 10 cm. The vegetation on the Severnaya Mine dump has a projective cover of approximately 25%. Tree cover consists of 10- to 15-year-old birches (*Betula*). A total of 9 plant species were recorded, including narrowleaf fireweed (*Chamaenerion angustifolium*), northern bedstraw (*Galium boreale*), green strawberry (*Fragaria viridis*), common haircap moss (*Polytrichum commune*), couch grass (*Elytrigia repens*), common yarrow (*Achillea millefolium*), sedge (*Carex*), and lady's mantle (*Alchemilla vulgaris*) (Table 1).

Table 1

List of vascular plants on reclaimed waste dumps

Family	Species name	Severnaya Mine Dump	Tsentralnaya Mine Dump	Gorelovskaya Mine Dump
Asteráceae	*Achilléa millefólium*	+	++	+
Rosaceae	*Alchemilla vulgaris*	+	++	–
Asteráceae	*Artemísia absínthium*	–	–	+
Asteráceae	*Artemísia vulgáris*	–	+	–
Gramíneae	*Brōmus inērmis*	–	++	–
Asteráceae	*Carduus crispus*	–	–	+
Cyperaceae	*Cárex sp*	++	+	-
Asteráceae	*Centaurea scabiosa*	–	–	+
Onagraceae	*Chamaenérion angustifolium*	+	–	+
Asteráceae	*Cichórium íntybus*	–	–	+
Asteráceae	*Cirsium arvense*	–	+	–
Gramíneae	*Dáctylis glomeráta*	–	+	–
Gramíneae	*Elytrígia répens*	+	+	–
Gramíneae	*Festuca pratensis*	–	+	–
Rosaceae	*Fragária víridis*	+	+	–
Rubiaceae	*Galium boreale*	+	+	+
Hyperiaceae	*Hypericum perforatum*	–	+	+
Fabaceae	*Lótus corniculátus*	–	+	+
Fabaceae	*Medicago falcata*	–	+	+
Fabaceae	*Medicágo satíva*	–	+	-
Fabaceae	*Melilótus officinális*	–	-	+
Gramíneae	*Phleum pratense*	–	+	+++
Asteráceae	*Picris hieracioides*	–	–	+
Gramíneae	*Poa praténsis*	–	+	+
Polytrichaceae	*Polýtrichum commúne*	+	–	–
Gramíneae	*Puccinellia distans*	–	–	+
Ranunculaceae	*Ranunculus repens*	–	–	+
Caryophylláceae	*Siléne vulgáris*	–	–	+
Asteráceae	*Tanacétum vulgáre*	–	+	+
Fabaceae	*Trifolium praténse*	n/a	n/a	+++
Plantaginaceae	*Veronica teucrium*	n/a	+	n/a
Fabaceae	*Vícia crácca*	n/a	+	n/a
Betulaceae	*Bétula péndula*	+	–20	–19

According to the WRB, the clay lithostrat identified on the Tsentralnaya Mine dump is classified as Spolic Epileptic Technosol (Loamic, Densic, Skeletic) (Fig. 2, *B*). The lithostrat lacks distinct horizons or layers, and there is an abundance of stones and coal (about 40%). Up to a depth of 10 cm, the structure is cloddy with herbaceous roots. The soil is dense, clayey, and brownish-brown in color. The vegetation on the Tsentralnaya Mine dump includes 20 species from the families *Gramineae*, *Asteraceae*, *Rosaceae*, *Rubiaceae*, *Fabaceae*, *Plantaginaceae*, and *Cyperaceae* (see Table 1). The projective cover is about 35%.

The clay lithostrat was also diagnosed on the Gorelovskaya Mine dump. According to the WRB, this soil can also be classified as Spolic Epileptic Technosol (Loamic, Densic, Skeletic) (Fig. 2, *C*). The soil is light brown, with blocky soil aggregates and a clayey texture. The lower part of the profile is moist with a plastic consistency. The vegetation on the Gorelovskaya dump includes 19 species. The dominant species are Timothy grass (*Phleum pratense*) and red clover (*Trifolium pratense*), while 17 species from the families *Gramineae*, *Fabaceae*, *Asteraceae*, *Caryophyllaceae*, *Onagraceae*, *Ranunculaceae*, and *Rubiaceae* are found sporadically (see Table 1). The projective cover is about 50%

Vegetation changes were identified using the NDVI index based on Sentinel-2 and Landsat 7,8 satellite images (Figs. 3–5). Succession on the coal waste dumps was analyzed over several time periods: the initial period (untouched dump), a few years after reclamation, and the state of vegetation in 2023.

For the Severnaya Mine dump, four observation periods were considered (see Fig. 3): the initial state of the dump, two years after reclamation, seven years after reclamation, and the current state. The NDVI index for the Severnaya Mine dump in June 2000 (before reclamation) was approximately 0.3. After reclamation, the NDVI index increased to 0.5–0.6, indicating the development of a stable vegetation cover.

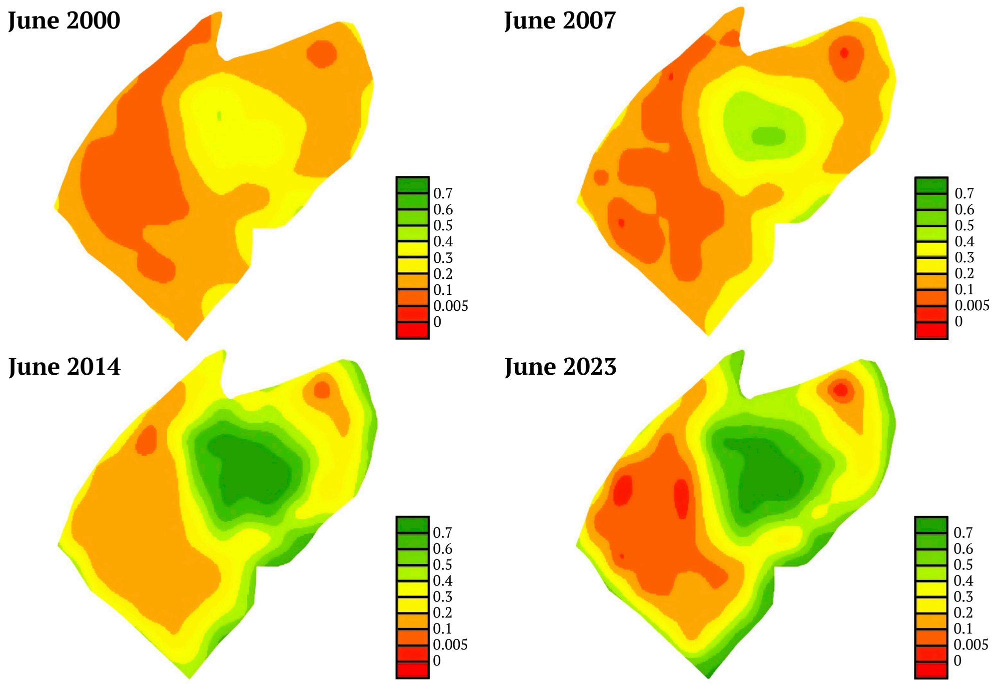

Fig. 3. NDVI Index for the Severnaya Mine Dump

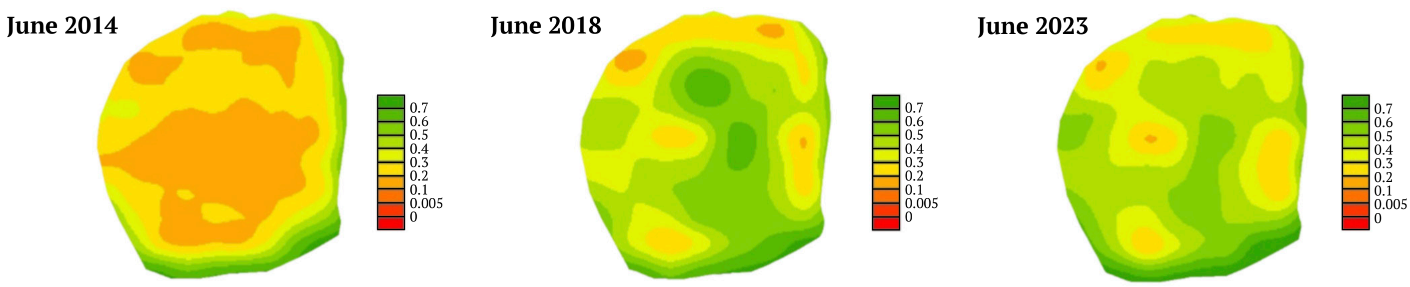

Fig. 4. NDVI Index for the Tsentralnaya Mine Dump

In June 2014 (before reclamation), the NDVI index for almost all areas of the Tsentralnaya Mine dump ranged from 0.1 to 0.3, indicating the absence of any vegetation (Fig. 4). Over the next 9 years, most of the dump area became covered by shrub vegetation, as reflected by an NDVI index value of around 0.4.

On the Gorelovskaya Mine dump, during the 5 years following reclamation, the NDVI index increased from 0.1–0.3 to 0.4–0.55, and even exceeded 0.6 in some areas (Fig. 5). The dynamics of the NDVI index across all three dumps indicate the success of reclamation efforts and the establishment of a stable vegetation cover.

Soil chemical properties

The surface layers of lithostrat 1 and the embryonic soil are characterized by a neutral pH, with pH–H_2O values of 6.8 and 7.9, respectively, and pH–KCl values of 4.4 in lithostrat 1 and 5.5 in the embryonic soil (see Table 2). At a depth of 20 cm, the soils become slightly acidic, with pH–H_2O decreasing to 3.3 in lithostrat 1 and to 5.0 in the embryonic soil. The surface layer of lithostrat 2 has a slightly acidic reaction (pH–H_2O = 6.1, pH–KCl = 4.1), with acidity increasing at depth, reaching pH–H_2O = 4.5 (see Table 1). The lower layers of lithostrat 1 contain sulfide minerals, as indicated by pH values in hydrogen peroxide (pH–H_2O_2 = 1.98) (see Table 2). This is due to the mixing of the lower soil layer with the upper layer of the dump material as a result of physical and chemical migration of substances.

Lithostrat 2 exhibits the highest exchangeable acidity among all the dump soils, attributed to the fact that the soil is formed from the middle horizons of local clay soils. Hydrolytic acidity in lithostrat 1 and the embryonic soil is significantly lower than in the background soil (see Table 2), which is explained by the neutral to slightly alkaline nature of the dump soils. The results of the Kruskal-Wallis test showed that the acidity of the embryonic soil differs from that of the background soil and lithostrats.

The content of mobile iron in the dump soils is 1.5–2 times lower than in the background soil (see Table 2). Sulfate ions dominate in the aqueous extracts of the soils, with the highest concentration found in lithostrat 1. The increase in mobile sulfur content with depth in the lithostrats is associated with the presence of overburden material at depths of 20–30 cm. In contrast, the content of mobile sulfur in the embryonic soil decreases with depth, while it increases in the lithostrats.

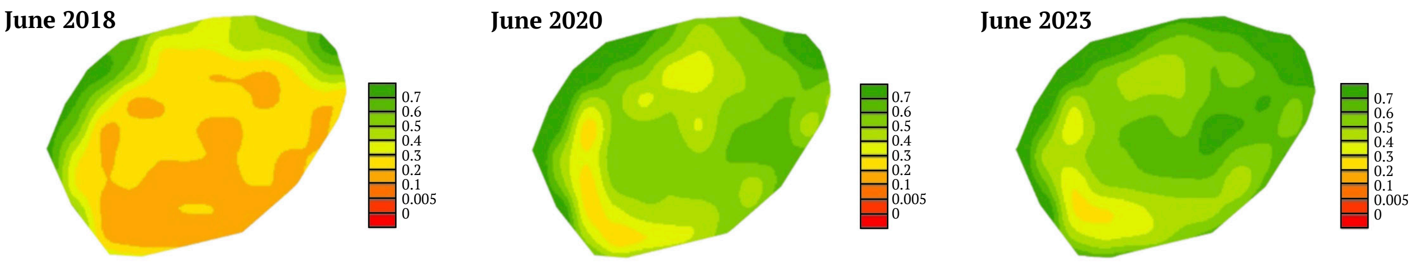

Fig. 5. NDVI Index for the Gorelovskaya Mine Dump

Table 2

Soil chemical properties

Parameters	Depth, cm	pH–H_2O	pH–H_2O_2	pH–KCl	$H_{гк}$*	OK** (Al^{3+}+ H^+)	Al_{exch}	Fe_{mobile}	S_{mobile}	SO_4^{2-}
					mmol/100 g			mg/kg		
Soddy embryonic soil	0–10	7.9	5.47	6.9	1.2	0	0.05	90	211.0	384.0
	10–20	7.4	5.41	6.3	1.2	0	0.05	220	163.0	480.0
	20–30	5.0	3.83	4.3	2.5	0.06	0.05	110	53.6	480.0
Lithostrat 1	0–10	6.8	4.41	5.3	3.9	0.08	0.05	250	17.0	312.0
	10–20	6.1	4.04	4.7	4.7	0.07	0.05	200	109.0	288.0
	20–30	3.3	1.97	2.6	16.3	2.33	3.98	260	253.0	816.0
Lithostrat 2	0–10	6.1	4.10	4.0	4.2	0.60	0.35	70	5.19	168.0
	10–20	5.1	3.80	3.7	15.2	8.40	9.37	110	20.8	240.0
	20–30	4.5	3.30	3.5	21.3	13.60	14.75	250	93.8	230.0
Background sod-podzolic soil	0–10	4.5	3.71	3.5	26.4	5.00	43.00	430	12.90	240.0
	10–20	4.6	3.88	3.5	21.4	5.90	52.00	430	4.60	240.0
	20–30	4.7	4.05	3.6	20.8	5.90	52.00	360	0.20	240.0

Note: * H_{ha} – hydrolytic acidity, ** *EA* – exchangeable acidity.

The organic matter content varies across soil types and layers (Table 3). The highest organic matter content was observed in the embryonic soil. The high organic matter content in the lower layer of lithostrat 1 is attributed to the abundance of coal, while the upper layers of lithostrat 1 contain 2–3 times less organic matter. In comparison to lithostrat 1 and the embryonic soil, lithostrat 2 exhibits the lowest organic matter content.

The cation exchange capacity of the soils is generally moderate, with the highest values in the upper 10 cm layer. The absorption capacity of the background soil is slightly lower, likely due to the presence of exchangeable calcium and magnesium cations. The exchangeable calcium content in the dump soils shows no significant variation and decreases with depth.

The phosphate content in the dump soils is lower than in the background soil and is classified as "low" according to the Kirsanov scale (see Table 3). The highest mobile potassium content is found in lithostrat 1, while the lowest is in the embryonic soil. The nutrient content in the soils is influenced by the duration of soil formation and the vegetation cover. The greatest variety of herbaceous plant species was observed in lithostrat 1 at the Tsentralnaya Mine dump, which may contribute to higher nutrient availability. All soils exhibit similar nitrogen content, except for lithostrat 2 (Table 3).

The upper soil layers of the dumps demonstrate more favorable conditions for test crops compared to the background soil (Fig. 6). Cress grown on lithostrat 1 and the embryonic soil showed significantly better results in terms of height and biomass compared to the control plants grown on vermiculite.

Oats grown in the control group on vermiculite reached the same height as those grown on the dump soils (Fig. 6, *b*). However, the biomass of oats grown in the control group was significantly higher than that of the plants grown on both the dump soils and the background soil.

Table 3

Agrochemical soil properties

Parameters	Depth, cm	Organic matter	Ca_{exch}	Mg_{exch}	EKO	K_{mobile}	$P_2O_{5mobile}$	N_{total}
		%	mmol/100 g			mg/100 g		
Soddy embryonic soil	0–10	12.1	5.75	0.56	37.0	7.0	2.5	311
	10–20	7.7	6.06	0.56	22.0	7.2	0.7	143
	20–30	9.2	4.25	1.00	19.0	2.8	0.09	70
Lithostrat 1	0–10	2.43	10.00	1.25	23.0	20.5	2.2	166
	10–20	3.11	7.60	1.13	24.0	10.4	3.1	93
	20–30	8.90	1.75	0.50	27.0	5.3	0.09	143
Lithostrat 2	0–10	1.04	16.75	6.25	27.0	10.4	3.0	47
	10–20	0.81	5.62	3.62	24.0	10.8	1.9	48
	20–30	1.01	4.75	1.12	28.0	12.0	3.0	49
Background sod-podzolic soil	0–10	5.04	3.25	1.25	13.0	15.4	29.7	187
	10–20	5.07	2.25	1.00	21.0	10.7	22.6	240
	20–30	6.10	2.75	1.25	19.0	8.8	7.5	228

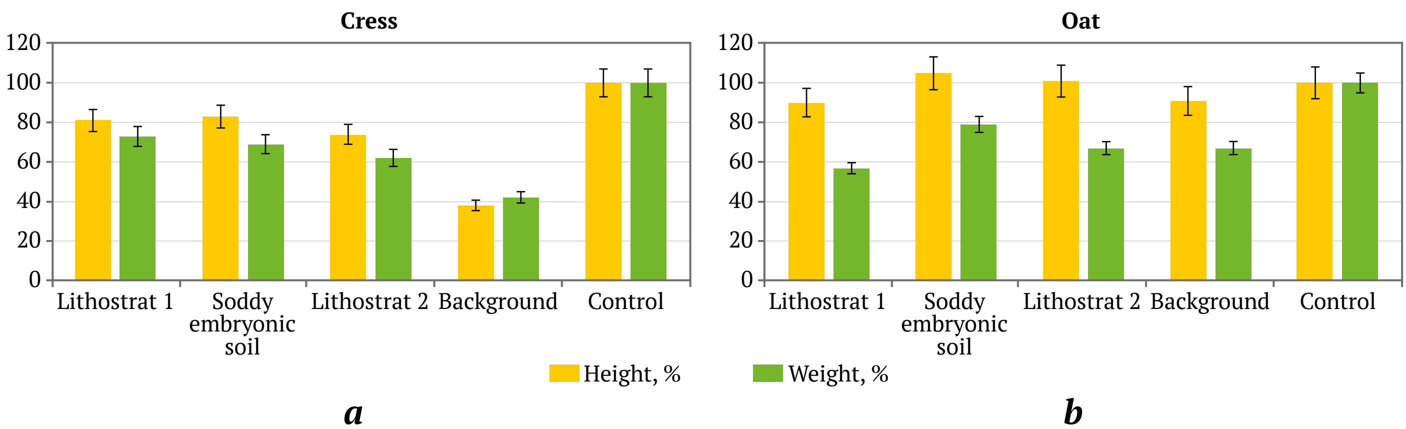

Fig. 6. Phytotesting of the upper soil layers

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Discussion

The lithostrats formed as a result of covering the flattened top of the coal waste dump with a layer of clay material, which appears to originate from the subsurface layers or parent material of the local soils. This is evidenced by the similar granulometric and aggregate composition. Iron coatings were observed on soil aggregates (peds) down to a depth of 20 cm. The profile depth of the lithostrats ranges from 30 to 40 cm, which is determined by the thickness of the clay deposit, the slope steepness of the dump, and the degree of fragmentation of the dump's overburden material.

The differences in acidity between the lithostrats can be explained by the fact that the reclamation of lithostrat 2 was completed several years later, and construction debris from former mining operations remained on the Tsentralnaya Mine dump, which may have led to the reduction of acidity in lithostrat 1. However, the strong acidity of the lower layer of lithostrat 1 is attributed to the presence of sulfides in the dump's overburden.

The embryonic soil formed on the crushed overburden of the leveled coal dump. To create favorable conditions for plant growth, slaked lime was added to the surface layer of the dump, making the soil slightly alkaline. The use of lime in waste dump reclamation is a common practice, as is the use of activated sludge as a fertile layer.

For instance, the combined use of beet lime and composted biological materials helped neutralize active and exchangeable acidity in soils and improve soil fertility at a copper mine site [15]. During the biological reclamation phase of the Kapitalnaya Mine in the Kuznetsk Coal Basin, sewage sludge from urban wastewater treatment plants was used as a fertile layer [29].

Primary soil formation processes are actively taking place in the soils of the Kizel Coal Basin (KCB) dumps. Vegetative cover, plant roots, and the annual formation of dead plant matter contribute to the loosening of the upper soil layer and the accumulation of organic matter.

Similar types of technogenic soils are formed under comparable conditions in other regions with coal mining, similar climates, and vegetation [3, 30, 31]. Technogenic soils on waste dumps are pedogenically immature and inherit the negative physicochemical properties of coal mine dumps [32], as well as containing a significant amount of artifacts.

The relatively high mobility of iron in the background soil compared to the dump soils may be due to the acidity and high content of iron hydroxides in the clay minerals of sod-podzolic soils [33, 34].

The low organic matter content in lithostrat 2 is due to the absence of fertilizer application during reclamation. Its organic layer has not yet developed because of the immaturity of the phytocenosis. The high organic matter content in lithostrat 1 can potentially be explained by the presence of coal inclusions throughout the profile, as well as a stable herbaceous community. The presence of coal particles in the overburden [35] could explain the high organic matter content in the embryonic soil (7.7–12.1%) and the lower layer of lithostrat 1(8,9%).

The amount of total nitrogen and mobile potassium increases with the age of the lithostrat, as confirmed by [36, 37]. Overall, the total nitrogen content in the lithostrats is significantly lower than in the background sod-podzolic soil and embryonic soil.

The coefficient of variation (CV) is explained by the influence of technogenic and anthropogenic processes on soil formation. Notably, the coefficient of variation for exchangeable acidity, organic matter, total iron, and mobile sulfur in the lithostrats exceeds 40%. In contrast, the range of CV for these indicators is significantly lower in the embryonic soil. This is due to the homogeneity of the parent material in the embryonic soil, while the lithostrats consist of a mixture of clay and the upper layer of the dump. As a result, the properties of the lower layers of the lithostrats do not correspond to either the characteristics of the overburden or the clay material. The coefficient of variation for most chemical indicators of the background soil does not exceed 25%, except for mobile sulfur content, where the CV reaches 110%, similar to the values for mobile sulfur in the lithostrats and embryonic soil.

Correlation analysis revealed a direct and significant relationship between hydrolytic acidity, exchangeable aluminum content, and mobile iron. The sources of iron in the studied technogenic soils are minerals from zonal soils and the overburden of the dumps. The amount of mobile phosphates is proportional to these indicators, possibly due to the ability of phosphates to form complexes with aluminum and iron under acidic conditions. At the same time, a negative correlation was found between absorption capacity and mobile iron.

Based on the growth indicators of oats, the embryonic soil showed the best biological conditions, as it has a neutral pH and is characterized by a high organic matter content.

Reclamation of coal dumps through the creation of a clay barrier or the addition of fertilizers to stimulate the growth of herbaceous or woody vegetation is critical for preventing water and wind erosion, as well as the spread of pollutants. It is also essential for establishing stable plant communities. The chemical properties of technogenic soils vary significantly across the profile compared to the background soil in the study area, as well as among themselves.

Reclamation activities at the Severnaya Mine dump, conducted 25 years ago, have resulted in the formation of soddy embryonic soil, and soil evolution continues. Reclamation activities at the Severnaya Mine dump, conducted 25 years ago, have resulted in the formation of soddy embryonic soil, and soil evolution continues. Reclamation with the addition of slaked lime has reduced soil acidity to neutral levels and increased organic matter content and absorption capacity. Given that a stable herbaceous-woody plant community has developed on the reclaimed soils, this reclamation method can be considered effective. The modification of the substrate by adding ash, slag, and sewage sludge has been studied on coal dumps in Brazil, showing promising results for growing bristle oat (*Avena strigose*) and corn (*Zea mays*) [38].

Covering dumps with clay material neutralizes the sulfide minerals in the overburden by creating a barrier that prevents water and oxygen from contacting the minerals and forming acid mine drainage. The studied lithostrats formed similarly but differ in age. The effectiveness of reclamation using clay to cover the dump can be assessed by comparing the initial condition of the dump soil (lithostrat 2) with the more mature soil (lithostrat 1). The number of plant species in the vegetation community increases over time. A diverse herbaceous community promotes the accumulation of organic matter in the upper soil layer and the formation of soil aggregates, which improves the physical properties of the dump soils, reduces acidity, and increases NPK content.

In the study by [39], soils were compared 5, 10, and 25 years after mining. In the soils of degraded coal mining lands, carbon and nitrogen reserves increased with the length of the reclamation period. This may also be attributed to the input of organic matter from the waste dumps. The physical properties of the soil improved over time. Finer fractions became dominant in the older dump soils. [18] reported an increase in plant biodiversity in long-reclaimed areas. [17] noted the beneficial effects of herbaceous plants on the physicochemical properties of soils during the reclamation of mining areas. Soil properties on reclaimed dumps, such as organic matter content, nitrogen, and phosphorus levels, improved over time following reclamation [40].

Overall, plant growth on sulfide coal dumps after reclamation prevents wind and water erosion, spontaneous combustion, and the spread of contaminants [41]. Based on a comparison of lithostrats of different ages, it is recommended that organic and mineral fertilizers be applied to the reclaimed soil. Agroamelioration measures (soil layer formation for plant growth, fertilizer application, and planting of herbaceous crops) help achieve optimal results [42].

Conclusions

Various soil types have been identified on the reclaimed waste dumps of the Kizel Coal Basin. The classification is based on the reclamation activities carried out and the technogenic soil-forming materials. Clay lithostrats, or Spolic Epileptic Technosol (Loamic, Densic, Skeletic), were found on the dumps reclaimed by surface leveling and covering with clay material. The embryonic soil, classified as Epileptic Technosol (Densic, Carbonic, Skeletic), formed over a nearly 25-year period after the coal dump was leveled and lime was applied to the upper layer.

The absence of horizons and a well-defined soil aggregate structure, along with the presence of numerous artifacts (fragments of overburden of various sizes) in the soils formed on coal dumps, indicates their technogenic origin and immature stage of development.

The acidity levels in the lithostrats ranged from acidic to neutral, with hydrolytic acidity decreasing over time following reclamation. The embryonic soil exhibits a slightly alkaline reaction, and exchangeable acidity is absent. Statistical analysis showed no differences between the pH in water and the pH in KCl of the lithostrats and the background soil. However, the level of exchangeable acidity in lithostrat 1 was lower than that in the background soil and lithostrat 2.

Since the embryonic soil formed from crushed overburden of coal dumps, it contains the highest amount of organic matter. The organic matter content in lithostrat 1 is higher than in lithostrat 2, which is attributed to the presence of coal inclusions throughout the profile.

Herbaceous vegetation contributes to the formation of soil structure, the accumulation of organic matter, exchangeable calcium and magnesium ions, and, as a result, the reduction of acidity. The nutrient content (NPK) also depends on the time of soil formation and plant species diversity. Phytotesting using cress and oats showed that the dump soils provide more favorable environmental conditions for plant growth compared to the background soil.

Overall, reclamation accelerates soil formation and the development of stable plant communities on waste dumps, while minimizing the spread of contaminants to other environmental components. According to the NDVI index, stable herbaceous vegetation was observed on the sulfide dump just two years after reclamation. During the reclamation period, it is essential to implement measures such as plowing and the application of organic and mineral fertilizers to create optimal conditions for plant communities.

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Information about the authors

Natalya V. Mitrakova – Cand. Sci. (Biol.), Senior Researcher at the Laboratory of Biogeochemistry of Man-made Landscapes, Natural Science Institute, Perm State National Research University, Perm, Russian Federation; ORCID 0000-0002-5571-7725, Scopus ID 57208284684, ResearcherID ABC-8334-2021; e-mail mitrakovanatalya@mail.ru

Elena A. Khayrulina – Dr. Sci. (Geograph.), Leading Researcher at the Laboratory of Biogeochemistry of Man-made Landscapes, Natural Science Institute, Professor of the Department of Cartography and Geoinformatics, Faculty of Geography, Perm State National Research University, Perm, Russian Federation; ORCID 0000-0002-9074-8551, Scopus ID 56029238900, ResearcherID J-8411-2014; e-mail elenakhay@gmail.com

Anna A. Perevoshchikova – Junior Researcher at the Laboratory of Biogeochemistry of Man-made Landscapes, Natural Science Institute, Perm State National Research University, Perm, Russian Federation; ORCID 0000-0003-1769-7740, Scopus ID 57694899800; e-mail aaperevoshchikova@yandex.ru

Natalya V. Poroshina – Cand. Sci. (Chem.), Senior Researcher at the Laboratory of Biogeochemistry of Man-made Landscapes, Natural Science Institute, Perm State National Research University, Perm, Russian Federation; ORCID 0000-0002-1761-6720, Scopus ID 57694163400; e-mail navit1@yandex.ru

Elizaveta E. Malyshkina – Research Engineer at the Laboratory of Biogeochemistry of Man-made Landscapes, Natural Science Institute, Perm State National Research University, Perm, Russian Federation; ORCID 0000-0002-7251-7637, Scopus ID 58017742100; e-mail thelionofcintra@gmail.com

Evgenia S. Yakovleva – Research Engineer at the Laboratory of Biogeochemistry of Man-made Landscapes, Natural Science Institute, Perm State National Research University, Perm, Russian Federation; ORCID 0009-0005-5344-7361; e-mail evyakovlevaa@gmail.com

Nikita A. Kobelev – Research Engineer at the Laboratory of Biogeochemistry of Man-made Landscapes, Natural Science Institute, Perm State National Research University, Perm, Russian Federation; ORCID 0009-0007-3129-5568; e-mail amst3rz@gmail.com

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