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Soil-Ecological Assessment of Recultivation at the Spoils of Coal Deposits

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Abstract

The article reports the geochemical characterization of soils, vegetation, and groundwater of the recultivated spoils of three coal deposits. Recultivation was carried out 30–40 years ago, and then the spoils were left for self-overgrowth without any additional measures. A common pattern for all sites is the presence of carbonaceous particles, their oxidation leads to an increase in temperature in the spoil rocks. The sum of biologically active temperatures exceeds the values for natural soils of undisturbed areas. Technogenic landscapes are characterized by a smaller share of moisture-loving forest and pratal species, compared to the reference areas. Hydrogeochemical anomalies practically do not go beyond the flooded borrow excavations of spoils. Reclamation by applying a fertile soil layer provides minimization of the negative effects associated with an increase in the temperature of spoil soils and accelerates the remediation of regional plant communities.

Keywords: coal spoil recultivation, heavy metals, occurrence forms, accumulation ratio of elements in plants, vegetation cover, hydrothermal conditions

INTRODUCTION

The mining industry causes one of the most intense actions leading to large-scale transformation of the environment. This effect has become most obvious since the middle of the XX century, when the transition from shaft mining to quarrying occurred for many mineral resources due to the development of powerful open-pit vehicles. Quarrying leaves vast open pits surrounded by the dumps of overburden rocks. Complete elimination of the technogenic impact and recovery of initial landscapes is often impossible due to economic and technological reasons. Recultivation of disturbed environments is something like a compromise between economics and nature conservation.

Coal mining has its own specific features which allow distinguishing coal among other fossils. On the one hand, the demand of economy for this resource makes coal open pits most widespread, but on the other hand, unlike for other fossils, residual content of coaly particles in the spoils does not cause the emergence of other pollutants onto the surface, while coaly particles themselves do not cause toxic effect on biota.

Russia occupies sixth place in the world in coal production. According to data of the Ministry of

Energy, Russia, the total productive capacity of coal facilities was 523 mln t in January 2022. Natural landscapes have been damaged or strongly affected over vast territories because of coal mining. Natural ecosystems have been replaced by rapidly growing regions of technogenic landscapes, new landscape and surface relief forms started to appear under the action of technogenic denudation and aggradation. Coal mining is carried out in Russia at 171 objects (among them, there are 54 coal mines and 117 open pits), and most of them are situated in Siberia (Kuzbass) and neighbouring regions. This is why the issues concerning open-pit recultivation and coal mining are of special relevance for this territory [1].

At present, many recultivation technologies are applied in order to recultivate soil and plant cover at lands degraded as a result of production [2]. However, recultivation efficiency depends on the climatic and natural conditions, and on the level at which local ecological facilities are involved in recultivation of degraded lands. In the 1980s–90s, recultivation through depositing a fertile soil layer (FSL) on the planed surfaces of coal wastes and forming soil-like artificial structures – technosoil [3], later called technosol [4], has become widespread. Meagre soil, referred to in the work as embryozem, is formed over non-recultivated regions composed of overburden rocks (technogenic eluvium) [3].

The goal of investigation is to analyse the processes involved in the formation of the major chemical properties and plant cover development on recultivated and non-recultivated regions of open coal pits.

EXPERIMENTAL

Investigation procedures

The elemental composition of solid samples was determined by X-ray fluorescence analysis using the synchrotron radiation recording with the Si(Li) detector at the station of elemental analysis of VEPP-3, INP SB RAS (Novosibirsk). Determination error for sole elements is within the range of 5–15 %. The mineral composition of the samples was determined by X-ray powder diffraction studies with the help of a DRON-3 diffractometer (NPP Burevestnik, Russia, CuK_α-radiation). In order to differentiate small-grained layered aluminosilicates, some samples were impregnated with ethylene glycol before determination.

The composition of soil particles was studied with the help of a scanning electron microscope MIRA 3 LMU (TESCAN Orsay Holding, Czech Republic) equipped with the microanalysis system INCA Energy 450+ Xmax-80 (Oxford Instruments Nanoanalisys Ltd., UK) in the analytical centre of multielement and isotope studies at the IGM SB RAS (Novosibirsk). Determination of the composition of minerals and glasses was made at the accelerating voltage of 20 kV, electron probe current 1.5 nA, the live time of spectrum accumulation 20 s. Under these experimental conditions, the random error of analysis was less than 1 rel. % for the content of petrogenic components more than 10 wt. %, up to 10 rel. % – for 1–10 wt. % concentration, and reached 30 rel. % in the vicinity of the lower detection limit, which was 0.2–0.3 wt. %.

To characterise the overall chemical composition of plants, thermal ashing in the muffle furnace at a temperature of 500–600 °C was applied.

At the site, a series of five model test grounds were arranged, so that the size of these grounds was 10 × 10 m, as accepted for the studies of grass communities [5]. The partial and total projective cover was studied, phytomass samples were collected in five-fold replication. The samples were immediately separated into fractions according to the ecological-cenotic identification. The geobotanic descriptions were analysed using the IBIS software developed by A. A. Zverev [6].

Investigation of the thermal properties of soils at the chosen objects was carried out with automatic temperature sensors Termokhron (Russia) with measurement error ±0.5 °C. To provide the most complete survey over the depth of root penetration and maximal propagation in the soils under study, as well as to assess the boundaries of the piled horizons, the sensors were placed at a depth of 5, 25, 35 and 55 cm. Temperature was recorded every 4 h during 24 h starting from midnight, from July 2019 till July 2020. Thus obtained data were used to determine the average diurnal temperature, which was then used to calculate the sums of biologically active temperatures (BAT), that is, the sums of temperatures above 10 °C.

Objects of investigation

The objects of investigation were the regions of spoils at three deposits, recultivated by means of covering with FSL ~30 years ago and left for self-overgrowth: the Chernogorskiy open-pit coal mine (the Chernogorskoye black coal deposit, the Republic of Khakassia), the Nazarovskiy open-pit mine (the Nazarovskoye brown coal deposit, the Krasnoyarsk Terriroty), the Listvyanskiy open-pit mine (the Bungur-Listvyanskoye black coal deposit, the Kemerovo Region – Kuzbass). According to the average data of many years (obtained during the years 2012–2020) from meteorological stations located in the closest vicinity to the objects of investigation, the regions where the deposits are situated differ from each other in the natural climatic conditions, first of all in the hydrothermal coefficient proposed by G. T. Selyaninov: in the dry steppe zone of Khakassia it within the range of 0.7–0.9, in the forest-steppe of the Kans-Achinsk Fuel and Energy Complex it is ~1, in the sub-taiga zone of Kuzbass it is 1.3–1.5 (Fig. 1). Hydrothermal conditions generally determine the plants in the surroundings of coal deposits, which indirectly affect self-overgrowth at the spoil and syngenesis of plant communities [7].

The initial soil-forming substrate of all three grounds is represented by a mixture of overburden and host rocks of coal deposits. Its characteristic feature is the presence of coaly particles as inclusions, so that their content may reach in some samples 5–7 %, less frequently – more than 10 % [8]. At the stage of spoil formation, the surface of all the ground was plain (levelled horizontally). After levelling, within recultivation, a fertile soil layer was deposited on the grounds. The soil layer was represented by humus-accumulating horizons of the zonal soils. The thickness of FSL layer is 20–30 cm. So, technozem-type soils were artificially formed on the recultivated grounds. At non-recultivated grounds, sod soil (at the spoils in Khakassia) and humus-accumulating soil (at the spoils in the Krasnoyarsk Territory and the Kemerovo Region) had been formed by the start of investigation. All the recultivated and non-recultivated grounds were left for self-overgrowth after the stages of surface formation.

During the time that passed since soil layer deposition, the grounds were covered with the vegetation, and fragmentary plant litter, represented by grey-brown semi-decomposed grass residues forming a layer up to 1 cm thick, was formed over almost all open pits. The litter is localised above the sod cover, which is 2–5 cm thick at different regions.

RESULTS AND DISCUSSION

Specificity of the soil cover at the spoils under investigation

Macromorphological investigation of soils shows that the common properties of technozem soils (artificially formed soil) include the presence of FSL deposited over the spoil surface, and this layer forms the basis of the root habitable layer. Its characteristic feature is the presence of lumpy-slabby structure in its lower part, which is the evidence of weak binding of the horizons in the newly formed soil layer and underlying rocks in the technozem soil.

At non-recultivated grounds formed on the substrates of coal pit spoils, the major feature of embryozem profile is substantial rockiness. However, during more than 30 years of spoil existence, rather thin (not more than 2 cm) and often fragmentary humus-accumulating horizons had been formed in the upper part of soil profile at the Nazarovskiy and Listvyanskiy coal openpits. These horizons are similar in their properties to the deposited horizons of FSL at recultivated grounds. Exclusions are non-recultivated spoils in Khakassia, where the described horizon is not present.

Geochemical characterisation of the emerging landscapes

Overburden and host rocks comprising the spoils are of sedimentary origin, so, in addition to primary minerals, also kaolinites, illite-smectites are widespread in the sections of initial technogenic eluvium. Comparing the photographs of sections of the fragments of unaltered techno-

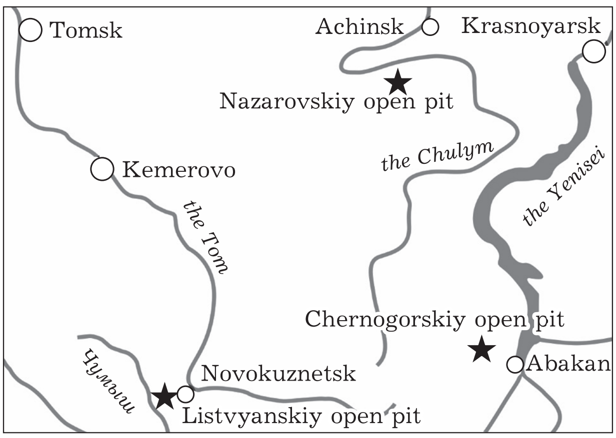

Fig. 1 Scheme of the location of objects under investigation.

genic eluvium (the fragments larger than 10 mm in size) and dust samples (the fraction >0.2 mm) one may note that separate grains of layered silicates, such as muscovite, chlorite, kaolinite, illite-smectite, were curved during diagenesis, and currently they are irregular fractured grains. Some sections contain the split grains of biotite and chlorite. In the dust fraction, plate-like aggregates are observed on some grains. These aggregates are likely to be illite-smectites. These grains were formed in the voids and do not have fractures or kinking characteristic of the grains that underwent diagenesis. It may be admitted that they were of modern origin after the rock was extracted to the surface.

Substantial amounts of carbonates including siderite, dolomite, and calcite are observed in the samples of unaltered eluvium. Carbonates are almost completely absent from the dust fraction [9]. Siderite dissolution may be described by the following equation:

$$2FeCO_3(s) + H^+ + CO_2(aq) + H_2O = 2Fe^{2+} + 3HCO_3^-$$

Carbonate ion is carried away with the solution, while iron may be oxidised to the three-valent state and precipitate *in situ* in the form of goethite or hydrogoethite. It has been demonstrated previously [10] that precipitation in the form of hexagonal plate-like crystals is the evidence of chemogenous genesis of these sediments.

Sulphides were detected in the fragments of rocks: pyrite, sphalerite, galena, smythite (iron and nickel sulphide $(Fe,Ni)_{3+x}S_4$ ($x = 0{-}0.3$)). Sulphides were not detected in the dust fraction, which is most likely due to their dissolution when they get into the subsurface conditions.

A general regularity for all grounds is the presence of X-ray amorphous component in technogenic eluvium. This component is represented by coal particles, causing the change in colour of this layer (Fig. 2). Oxidation of these particles by atmospheric oxygen is accompanied by energy release, which causes temperature rise in the rocks of the spoil. The addition of coal particles into the substrate may cause a decrease in the oxidation-reduction potential of soil sections in the long-term period.

For the main soil types, stepwise leaching was carried out according to the procedure proposed by Tessier [11]. This allowed us to distinguish four groups of elements. The first group includes alkaline metals (Na, K, Ca, Na, Sr), which are mostly present in the exchange fraction (up to 66 %); these elements are readily accessible for plants. The second group includes amphoteric elements (Al, Fe, P, Ti), they are mainly present in the organic fraction (60–90 %). The elements of the third group (Cr, Ba, V, Zn, Rb,) are present mainly in the insoluble fraction (70–92 %), which suggests that these elements are included into the crystal structures of primary and secondary metals. The fourth group of elements is not related to any fraction (Cu, Co, Ni, Eu); these elements are distributed among three fractions: the fraction related to Fe and Mn oxides, organic, and insoluble.

Some elements were analysed in soils and in plants (Fig. 3), which allowed us to estimate the

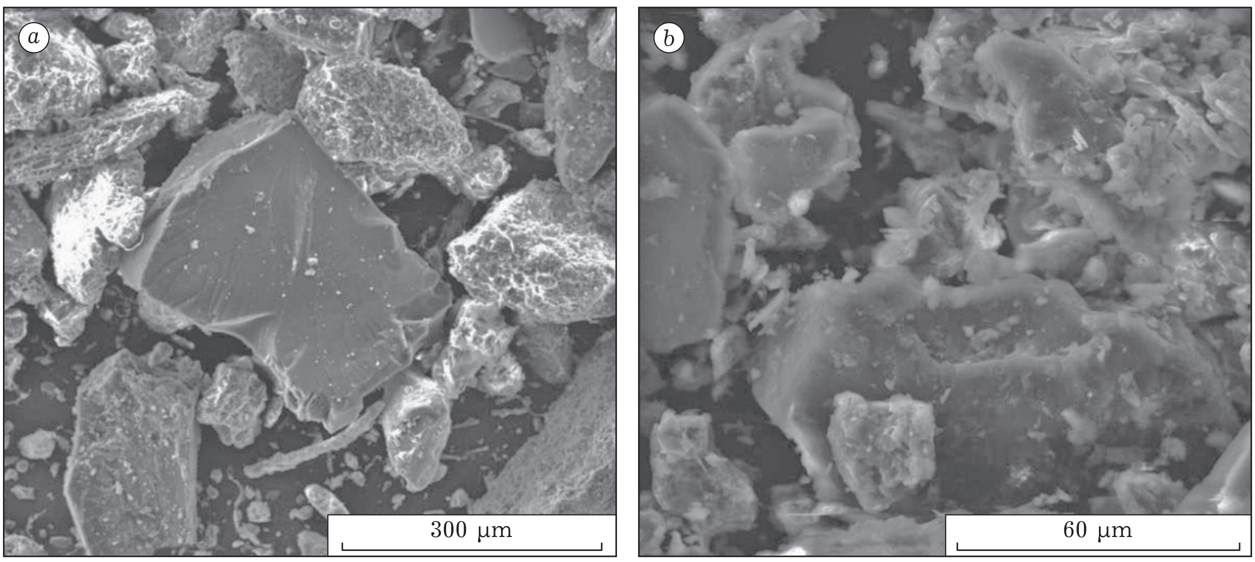

Fig. 2. Photographs of coaly particles in the technogenic eluvium of the grounds at the Chernogorskiy (*a*) and Listvyanskiy coal mine spoils (*b*) [9].

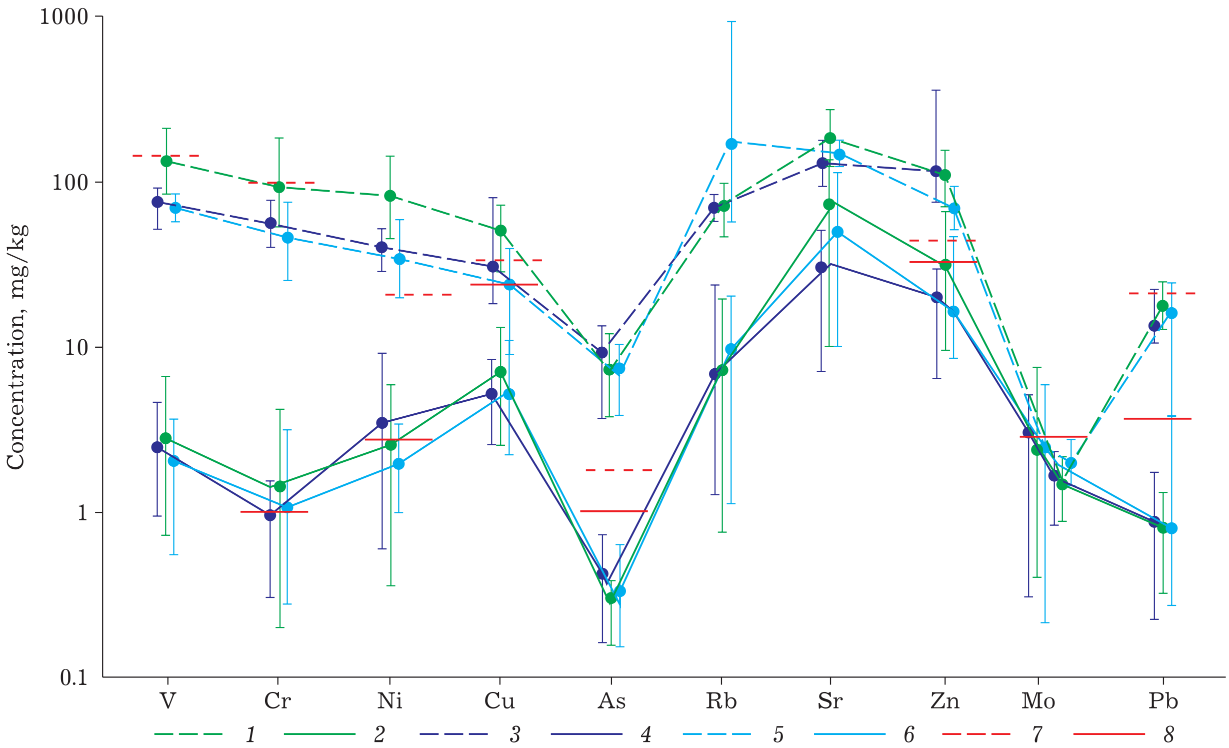

Fig. 3. Distribution of chemical elements in soils and plants at the studied grounds (average values, concentration range). Designations: *1* – Listvyanskiy, soils; *2* – Listvyanskiy, plants; *3* – Nazarovskiy, soils; *4* – Nazarovskiy, plants; *5* – Chernogorskiy, soils; *6* – Chernogorskiy, plants; *7* – MAC of chemical elements in soil [12]; *8* – MAC of chemical elements in forage for agricultural animals [13].

biological absorption factor (BAF). Three groups of elements may be distinguished: 1) Cr, V, Pb, As, Ni, Rb are not absorbed in plants, BAF for some regions is 0.01–0.1; 2) Sr, Zn and Cu are absorbed moderately (BAF = 0.2–0.4); 3) elements with active biological absorption (BAF = 0.8–1.1), only Mo relates to this group.

Comparison with the existing maximum allowable concentrations (MAC) in soil allows us to conclude that nickel concentration is 1.7–7.1 times higher than the MAC for soil, copper – 1.3–2.6 times, arsenic – 4.7–6.1 times, zinc – 1.2–2.5 times. The excess is observed both in natural and in newly formed soils and is caused by an increased background content of these elements. In comparison with MAC, the excess in forage for agricultural animals is observed only for chromium (1.5–3.9 times) and nickel (1.8–3.0 times).

Thermal properties of soils

Investigation of the thermal properties of the chosen objects shows that the maximal BAT sums (the sums of temperatures above 10 °C) are characteristic of technozems and embryozems formed on the spoils of the Chernogorkiy open-pit coal mine (Fig. 4, *a*). Here the calculated BAT sum exceeds the values for natural soils of undisturbed regions by more than 1000 °C. Downward along the profile, BAT sums increase reaching anomalous values at a depth of 35 cm in technozems – 3800 °C, in embryozems – 5800 °C. It may be assumed that lower, at a depth of 55 cm from the soil surface, soil temperature is substantially higher because the sensors were damaged, and we failed to take the readings from them.

Under the conditions of forest-steppe in the Krasnoyarsk Territory, where the spoils of the Nazarovskiy brown coal open pit were studied, we did not record any temperature anomalies similar to those observed at the spoils of Khakassia. Nevertheless, BAT sum in the upper part of the profile of these soils remained higher by 180–450 °C in comparison with the natural soils and the surface air layer (see Fig. 4, *b*). The maximal excess is detected in humus-accumulating embryozems, and the minimal one is observed in humus-producing technozems. A decrease in BAT sum with an increase in depth is detected. The BAT sums in technozems at a depth of 25 cm and deeper become equal to the values for black soil (chernozem). Embryozems also exhibit a decrease in temperature with depth, however, no so clear-

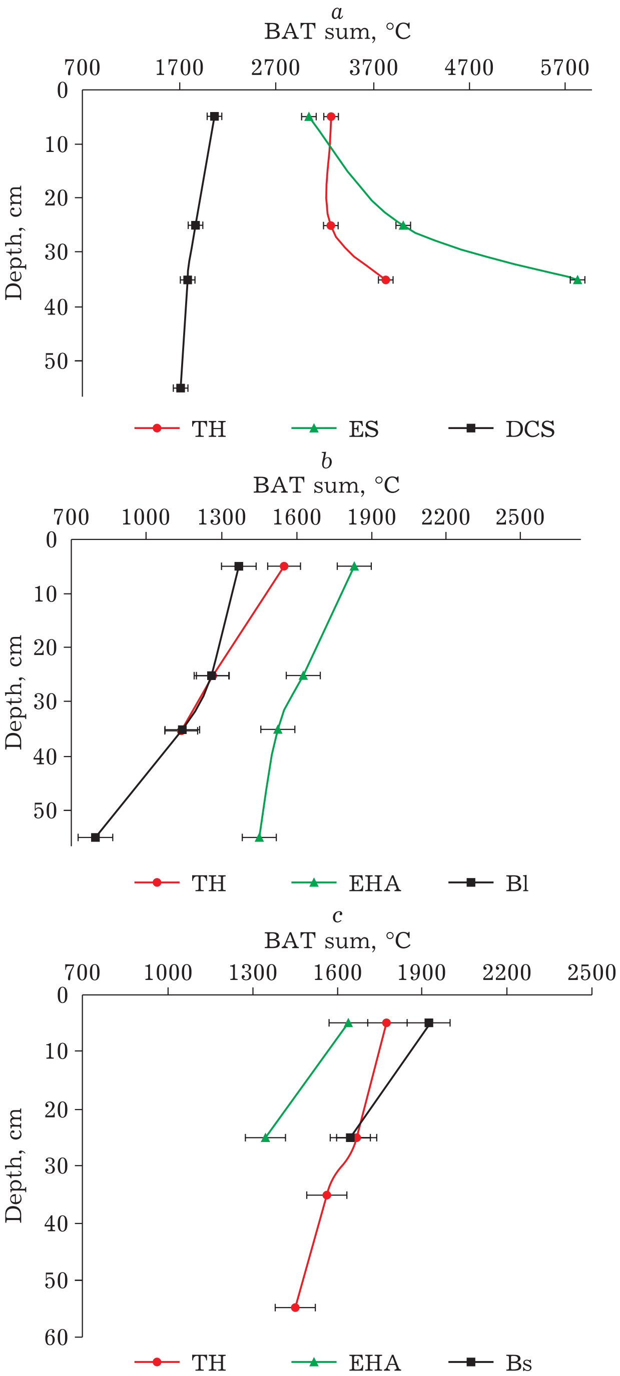

Fig. 4. Distribution of the sums of biologically active temperatures (BAT) over the profile of the soils of coal deposits: Chernogorskoye (*a*); Nazarovskoye (*b*); Listvyanskoye (*c*). Designations: TH – technozen, humus-accumulating; ES – embryoizem, sod; DCS – dark-chestnut soil; EHA – embryozem, humus-accumulative; Bl – black soil, leached; Bs – black soil, sod.

ly pronounced, because BAT sums remain higher by 350–650 °C than the values for black soil.

Under the conditions of sub-taiga in the Kemerovo Region, where the spoils of coal deposits were investigated similarly to Khakassia, BAT sum in the upper part of the profile of technogenic soil was lower than in natural soil (see Fig. 4, *c*). The values of BAT sums in the podzolic black soils were higher than the corresponding values for embryozems and technozems by 150–300 °C. The values of BAT sums in the soils under investigation sharply decrease with depth, their difference varies from 100 °C in technozems to 300 °C in embryozems. Similarly to the soils of the Nazarovsliy coal pit spoils, the values of BAT sums in technozems and black soil become practically equal at a depth of 25 cm.

Characterisation of plant cover

At the spoils of the Chernogorskiy open pit without FSL, the grass stand is mosaic, represented by the simple plant group. The basis of the projective cover is formed by *Calamagrostis epigeios* (L.) Roth (up to 70 %). Weeds are highly active: *Elytrigia repens* (L.) Nevski (up to 80 %), *Artemisia vulgaris* L. (up to 40 %), *Cirsium setosum* (Willd.) Bess. (up to 30 %), *Carduus nutans* L. (up to 5 %). Other kinds are present as sole plants. The total number of species is 20.

At the grounds with FSL, weeds are still prevailing, but the importance of steppe species increases: *Allium senescens* L. (up to 20 %), *Vincetoxicum sibiricum* (L.) Decne. (up to 10 %), forming local clusters. There are 21 species as a total.

At the fallow old-arable soils, the zonal steppe formations are being recovered, with the prevalence of *Poa stepposa* (Krylov) Roshev. (up to 20 %), *Helictotrichon desertorum* (Less.) Nevski (up to 20 %), *Potentilla longifolia* Willd. ex Schltdl. (up to 20 %), *Stipa capillata* L. (up to 5 %), *Galium verum* L. (up to 5 %), *Medicago falcata* L. (5 %) and others, with the presence of weeds: *A. vulgaris* (up to 40 %) and *Linaria vulgaris* L. (up to 10 %). The total number of species is 31.

At the spoils of the Nazarovskiy open pit without FSL, dominating species are *Poa pratensis* L. (up to 40 %), *Equisetum arvense* L. (up to 15 %), *Achillea millefolium* L. (up to 5 %), *Medicago lupulina* L. (up to 5 %), *Vicia amoena* Fisch. (up to 5 %), *Vicia cracca* L. (up to 5 %), the prevailing weeds are *Melilotus officinalis* (L.) Lam. (up to 30 %) and *Tussilago farfara* L. (up to 10 %), which is characteristic of the initial stage of functioning of complex pratal groups. The total number of species is 40.

The regions with FSL are characterised by the prevalence of *P. pratensis* (up to 70 %), codominants of the grass stand are *E. arvense* (up to 20 %), *Geranium pratense* L. (up to 5 %), *Thalic-*

trum simplex L. (up to 5 %), *V. cracca* (up to 5 %), *G. verum* (up to 10 %) and *Pimpinella saxifraga* L. (up to 5 %), *etc.* Other zonal species form not more than 1–2 % of the projective cover each, but they are uniformly distributed over the area. Weed species are present in sole samples, which allows us to characterise these pratal formations as closed phytocenoses. The total number of species is 34.

The basis of the grass stand at undisturbed forest meadows is formed by the pratal-forestal species: *Brachypodium pinnatum* (L.) Beauv. (up to 20 %) and *Heracleum dissectum* L. (up to 10 %), and the pratal species *Bromopsis inermis* L. (up to 30 %). Among the meadow-steppe species, the most pronounced is the participation of *G. verum* (up to 5 %), and semi-parasitic species *Rhinanthus autumnalis* L. is also widespread (up to 50 %). Among steppe species, a clearly pronounced assectator is *Vicia unijuga* A. Br. (up to 5 %). The total number of species is 40.

At the regions of the Listvyanskiy open pit without FSL, sharply dominating are pratal gramineous plants: *Dactylis glomerata* L. (up to 60 %), *Festuca pratensis* L. (up to 15 %), *Phleum pratense* L. (up to 10 %), *Agrostis gigantea* L. (up to 3 %), and *Poa angustifolia* L. (up to 1 %), legumes: *Amoria repens* (L.) C. Presl. (up to 2 %) and *V. cracca* (up to 2 %), and the representatives of herbage: *Potentilla canescens* Bess. (up to 3 %), *A. millefolium* (up to 2 %); other pratal species account for less than 1 % each. Among the meadow-steppe species, *P. saxifraga* (up to 20 %) and *Centaurea scabiosa* L. (up to 10 %) occur. Prevailing weeds include *Convolvulus arvensis* L., *Taraxacum officinale* L. (1 % each), other species occur in sole samples. Forestal species do not occur. The total amount of species is 38.

At the spoils with FSL, prevailing are meadow-steppe species *C. scabiosa* (up to 30 %), *P. saxifraga* (up to 30 %), *Fragaria viridis* L. (up to 30 %), pratal species *F. pratensis* (up to 40 %), *Galium mollugo* L. (up to 10 %), *A. millefolium* (up to 5 %), *P. canescens* (up to 5 %), *D. glomerata* (up to 2 %), *Leucanthemum vulgare* L., *Poa pratense*, *Trifolium pratense* L., *V. amoena*, *V. cracca* (по 2 %). Among weeds, the most active species are *Malva neglecta* Wallr. (up to 2 %) and *T. officinale* (up to 2 %). The total number of species is 53.

At fallow lands, the basis of grass stand is formed by the species *D. glomerata* (up to 60 %), *V. amoena* (up to 40 %), *P. pratensis* (up to 15 %) – in the upper sublevel, *F. pratensis* (up to 15 %) and *P. angustifolia* (up to 15 %) in the lower sublevel. The species that occur with smaller projective cover but uniformly over the whole area include *A. millefolium* (up to 5 %), *T. pratense* (up to 3 %), while the species occurring in clusters is *B. inermis* (up to 3 %). Semi-parasitic species *Rhinanthus vernalis* L. is present (up to 5 %). In comparison with spoils, the fraction of forestal species increases: *Fragaria vesca* L. (up to 5 %) and *Chamerion angustifolium* L. (up to 3 %). Among weeds, prevailing species are *T. officinale* (up to 3 %) and *Pastinaca sylvestris* L. (up to 1 %). The total number of species is 45.

As far as the species abundance of plant groups is concerned, a trend is revealed to increasing the number of species with an increase in the hydrothermal coefficient at the localities: the number of species observed at the regions without FSL of the Chernogorskiy open pit is two times smaller than at the regions of the Nazarovskiy and Listvyanskiy open pits (Fig. 5). Comparison between the grounds with FSL at different regions reveals the maximal increase in the species abundance with an increase in humidity: in comparison with the Chernogorskiy open pit, the number of species at the Nazarovskiy open pit is 1.6 times higher, while at the Listvuanskiy open pit the number of species is 2.5 times higher. In general, the number of species growing at the spoils of the Chernogorskiy open pit is 1.5 times smaller than at a reference ground located in the vicinity, while at the Nazarovskiy and Listvyanskiy open pits the differences in species abundance between the spoils and reference grounds are insignificant. In turn, at the ground with FSL at the Lisvyanskiy open pit, the number of species is even higher than that at the reference ground by 17 % [14, 15].

The most important factor demonstrating the direction of progressive succession is the ecological-cenotic structure of the grass stand (Fig. 6). The fraction of ruderal species in the projective cover fo the spoils at the Chernogorskiy open pit is 4.1–6.7 times higher than at the reference ground, and the fraction of the zonal group of steppe species is 2.3 lower at the grounds with FSL, and steppe species do not take part in the projective cover at the grounds without FSL.

At the spoils of the Nazarovskiy open pit, the fraction of pratal species in the projective cover reaches the background values, while at FSL it even exceeds them by a factor of 1.4. However, the participation of forestal species, accounting for more than 1/5 of the projective cover in the grass stand at the reference ground, is not pronounced at spoils. The lowest projective cover by

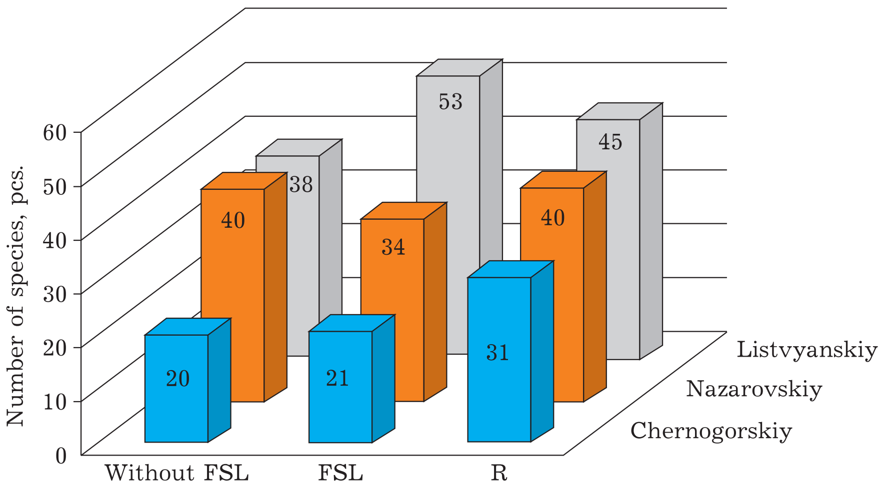

Fig. 5. Number of species at the model grounds: Listvyanskiy, Nazarovskiy, and Chernogorskiy. Designations here and in Fig. 6: FSL – fertile soil layer; R – reference ground.

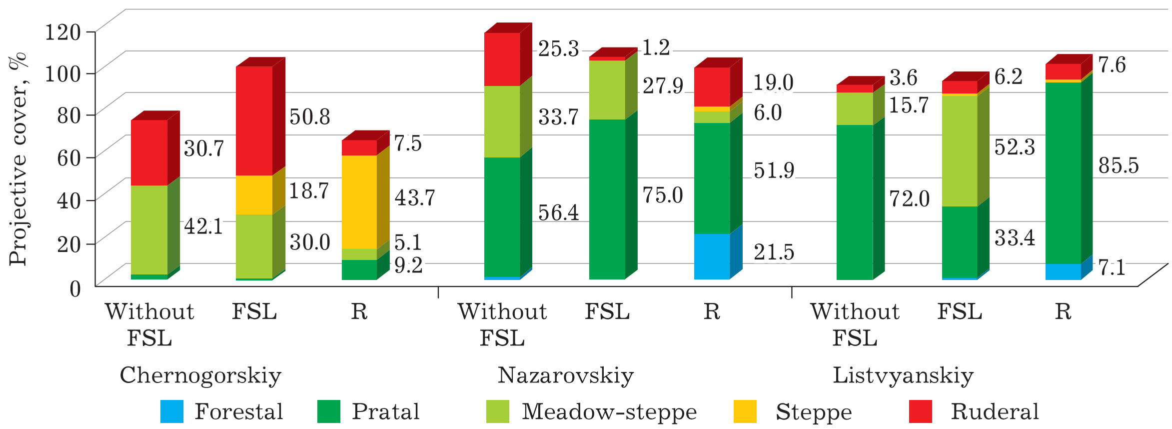

Fig. 6. Projective covers for ecological-cenotic groups at the Chernogorskiy, Nazarovskiy, and Listvyanskiy open pits. For designations, see Fig. 5.

ruderal species is detected at the Listvyanskiy open pit, so that at spoils it is 1.2–2.1 times lower than at the reference ground; with the high extent of pratal species participation, the group of meadow-steppe species is distinguished (15.7–52.3 %), which is not characteristic of the background (reference) ground, while forestal species also are not pronounced in the projective cover of the spoils.

Ground waters of open pit mines

At the grounds under consideration, the productive coal beds are located lower than the aquifer level, which is opened by the mining facilities. Entering waters are pumped out during coal extraction to avoid pit flooding. After the pits are removed from service, if recultivation does not involve pit liquidation, a lake is formed at the site of the pit. The lake is fed both by surface and ground waters. For the grounds under consideration, the chemical composition of ground water is formed through contributions from the soil and rocks of the spoil, which are highly permeable for atmospheric precipitation due to high dispersity.

The natural waters of the described climatic zones are hydrocarbonate sodium-calcium, with mineralisation (total dissolved solids) up to 1 g/L. One can see in the diagrams shown in Fig. 7 that the waters of open pits are characterised by a noticeable increase in the concentration of sulphate ion, in some cases it becomes the most abundant among other ions; the fraction of sodium in the cation composition increases (the Chernogorskiy region), waters of other grounds are magnesium-calcium in chemical composition. The waters are mainly alkaline, with pH within the range 6.5–8.3; mineralisation varies from 0.3 to 3.5 g/L. The MAC for iron and manganese are exceeded in the waters, which is a characteristic feature of the region under investigation [16]. Among heavy

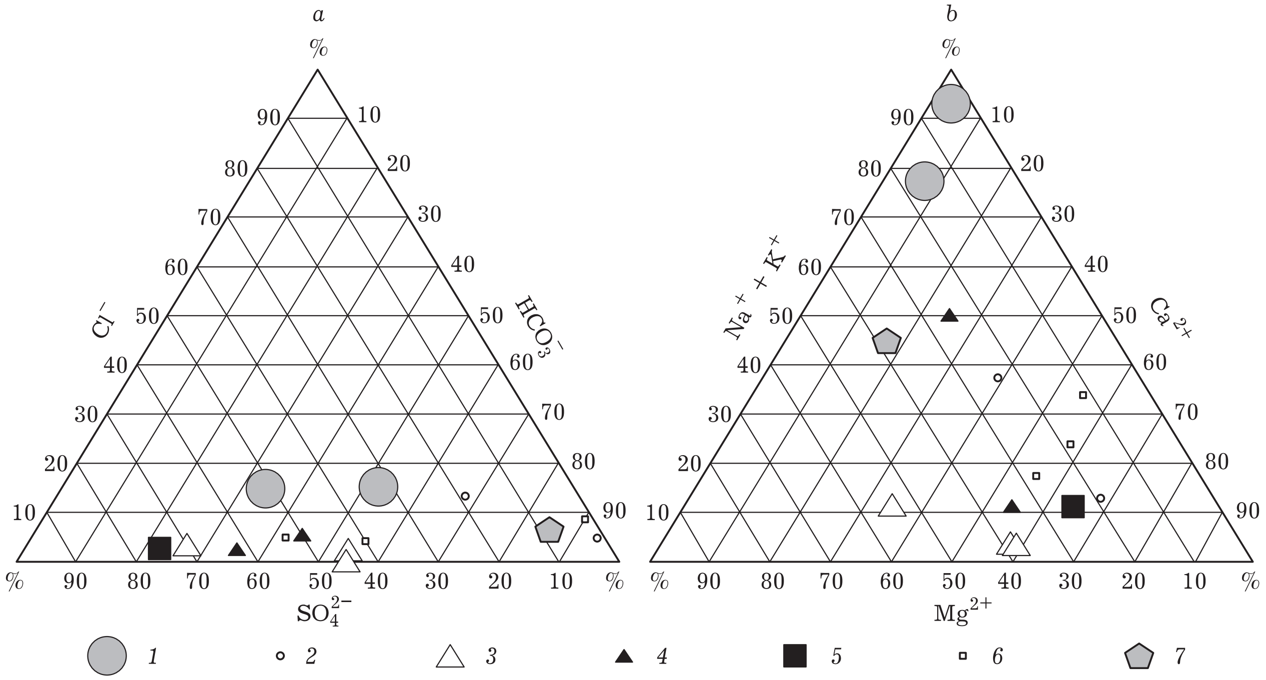

Fig. 7. Anion (a) and cation (b) composition of pit waters. Designations (ground, mineralisation): *1* – Chernogorskiy, >3000 g/L; *2* – Chernogorskiy, 0–500 g/L; *3* – Listvyanskiy, 1000–3000 g/L; *4* – Listvyanskiy, 500–1000 g/L; *5* – Nazarovskiy, 1000–3000 g/L; *6* – Nazarovskiy, 0–500 g/L; *7* – Averaged chemical composition of groundwaters [16].

metals, Ni concentration is detected to exceed the MAC (~20 %) only in sole samples.

The formed hydrogeochemical anomalies do not go outside the boundaries of flooded pits. In the cases is water streams flow out of these lakes, they are very rapidly diluted when mixed with other brooks, and their composition becomes undistinguishable from background water streams.

Effect of the temperature regime of spoil soils on the recovery of soil cover

The concentrations of most elements in technogenic sediments fit within the range observed in soil sections that remain unaffected by technogenic transformations. In some cases, technogenic transformations caused an increase in the local background for some elements, but the formed excess did not go beyond the regional background [17, 18]. Investigations show that the formation of overburden rock dumps during the management of coal deposits does not cause the formation of large geochemical anomalies on the surface. Extracted rocks contain a small amount of coaly particles.

Mineralogical alteration was detected in the rocks extracted to the surface: dissolution of sulphides and decomposition of carbonates (siderite and dolomite). During siderite decomposition, iron precipitated *in situ* in the form of goethite or hdyrogoethite. The waters of water bodies that have been formed at the foot of spoils exhibit increased mineralisation (up to 3.5 g/L). Sulphate content increases.

Evaluating the parameters of temperature regime for the soils under investigation, we may state that the soils formed on the spoils of coal embedding rocks are generally characterised by higher heat supply in comparison with natural (zonal) soils. This is pronounced to the highest extent at the Chernogorskiy coal open pit mine in Khakassia, where BAT sums for the upper (0–5 cm) layer of technozems and embryozems are higher by 1000–1200 °C than for natural soils. Anomalous high temperatures detected in the lower horizons provide evidence of the igneous processes taking place in the spoil. Since self-ignition processes at a spoil affect regions located at rather large distances from each other (recultivated – with technozems, and self-overgrowing – with sod embryozems), it may be concluded that self-ignition manifests itself over the whole spoil thickness.

In the spoils of the Nazarovskiy open pit mine, composed of loose sedimentary rocks, the specificity of the thermal regime of soils is likely to be connected with the features of watering, determined by the higher water retention in the humus horizons of technozems and black soil. In embryozems, devoid of these horizons, the soli profile is heated faster and more uniformly. As a result, BAT sums in embryozems are higher than in black soil and technozems by 200–450 °C.

Under the conditions of sub-taiga in Kuzbass, BAT sums in the 0–5 cm layer of natural soils are higher than in the soils of technogenic landscapes. It is evident that the temperature regime of soils has been substantially affected by the high pasture load on natural non-disturbed soils and the moderate load on regions with FSL deposited. At the grounds with self-overgrowth, where the above-ground phytomass is not removed because of the absence of pasture, the BAT sum of the upper part of soil in embryozems was minimal among the studied soils. So, evaluating the above-described features of the temperature regime of soils under investigation, we may reveal specific factors determining it. First of all, this is the general geothermal state of the landscape, depending on whether the object under consideration is subjected to self-ignition processes, how deep these processes take place, and what part is affected by pyrogenesis. The second factor is the state of plant communities, depending both on the species composition and on the mode in which the disturbed territories are used. The third factor is the influence of the colour of soil-forming substrate, determined by the amount of coaly inclusions in it, on the thermal regime of soils at the initial stage.

The features of the temperature mode of embryozems are depicted in the ecological-cenotic structure of the living soil cover. For instance, at the spoils of Khakassia, where the zonal xeromorphism is enhanced by the most substantial excess of BAT sum (with respect to reference grounds), some inhibition of the formation of plant groups is observed at the stage of simple phytocenoses, as a consequence of the domination of ruderal component. It should be stressed that the deposition of FSL on the spoils of Khakassia promotes an increase of only the quantitative parameter of the grass stand, that is, its total projective cover, but it does not provide qualitative improvement of the species composition, which is an inherent sign of ecosystem recovery. So, plant successions at the spoils of Khakassia (both with deposited FSL and without it) do not lead to the formation of plant cover approaching the characteristics of the initial one.

Under the conditions of forest-steppe in the Krasnoyarsk Territory, the species abundance of the grass stand at spoils is comparable with that at the reference grounds, which is the evidence in favour of growing conditions both on FSL and without it. However, some excess of BAT sum in the surface layer of embryozems is accompanied by the conservation of the high fraction of ruderal species and almost complete absence of forestal grass species, as the latter require substantial mesophytisation of the root habitable horizon. As a result, this promotes the formation of grass communities with the internal structure shifted by one step to xeromorphisation in comparison with the regions with natural recovery of post-arable land at zonal soils.

More favourable temperature regime of embryozems in the zone of sub-taiga in Kuzbass promotes the formation of grass phytocenonses on spoils. These phytocenoses are not inferior to self-overgrown fallow land but even surpass the latter in species abundance and in the structure of projective cover. A decrease in BAT sum is likely to promote better conservation of moisture in the surface soil layer, which provides more favourable water-air regime for pratal species to grow, in comparison with the conditions of zonal grey forest soil. The absence of a substantial number of forestal species in the projective cover may be explained by the larger distance from spoil sites to natural forests in comparison with the reference grounds, rather than the hydrothermal features of embryozems themselves. So, the course of progressive successions of the living soil cover during self-overgrowing of spoils in the sub-taiga regions of Kuzbass corresponds to the natural one, while the formed phytocenoses are close in their characteristics to zonal ones.

CONCLUSION

Investigation of the sites of spoil recultivation allowed us to draw the following conclusions.

The geochemical background of the formed systems does not exhibit any substantial differences from the background values for the regions adjacent to those under observation. The presence of coal particles in the technogenic eluvium and their oxidation cause temperature rise in spoil rocks. In the long-term outlook, the addition of coal particles into the substrate may cause a decrease in the oxidation-reduction potential of soil sections, which will affect the conditions for elements migration. The effect of the admixture of coal particles in the section will also affect heat evolution as a consequence of the oxidation of these particles by atmospheric oxygen. Mineralogical transformations detected in the section are mostly of scientific significance rather than of practical importance. Hydrochemical anomalies that are formed at the open pits are rather local; water streams flowing out of these lakes very soon become indistinguishable from the nearby brooks due to dilution with background water streams.

In the formed soils and plant cover, concentrations of Ni, Cu, As and Zn are detected to exceed the MAC level, which is connected with the initial background for these elements. As a rule, background (reference) soils contain higher concentrations of these elements than embryozems and technogenic eluvium. The concentrations of these elements in technogenic eluvium and in loamy sand used as FSL are lower than in soil-forming substrates of background soils.

Temperature rise in technozems and embryozems evidently affects the consumption of atmospheric precipitation and evaporation, thus affecting water availability for plant communities formed at the spoils. For this reason, all technogenic landscapes under investigation are characterised by a lower fraction of moisture-loving forestal and pratal species. Recultivation through FSL deposition promotes minimisation of negative effects connected with temperature rise in the soil of spoils, and acceleration of the recovery of zonal plant communities. Application of the FSL cover on disturbed surfaces promotes a decrease in BAT sum for technozems and approaches these values to those characteristic of zonal soil. This is most noticeable in the forest-steppe at the spoils of the Nazarovskoye brown coal deposit, where the formation of a root habitable layer promotes a decrease in BAT sum by 300 °C at a depth of 5 cm and achievement of the values typical for zonal soils at a depth of 25 cm. At the spoils of the Kans-Achinsk complex, grass phytocenoses are undergoing restoration, but with a shift toward xenomorphism.

Under the conditions of increased humidification in the sub-taiga of the Kemerovo Region, the soils of technogenic landscapes at the spoils of the Listvyanskoye black coal deposit are characterised by lower sum of active temperatures than the natural ones. However, in this layer, too, the formation of an artificial root inhabitable layer with FSL deposition causes an approach of BAT sum to the zonal level, which is most probably a positive factor affecting an increase in the number of plant species. Recovery of phytocenoses at the spoils with FSL in the sub-taiga of Kuzbass corresponds to the same process at fallow lands.

A smaller degree of the positive effect of FSL deposition is exhibited at the spoils of the Chernogorskiy open pit coal mine in the steppe zone of Khakassia, which are prone to self-ignition. Anomalously high BAT sums increasing with depth not only have a negative effect on the species diversity of plant communities but also minimize the fraction of steppe zonal species, which are characterised by the development of extensive root systems. The formation of an artificial root inhabitable layer at the spoils promotes settling and fixing the meadow-steppe species, which dominate in natural landscapes. At the spoils of Khakassia, the recovery of phytocenoses does not occur even after FSL deposition. Additional measures are necessary for full-value recultivation, in particular the introduction of seeds related to steppe variety above FSL. This approach was tested for the steppe landscapes of Kuzbass, where it demonstrated its efficiency [19].

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