The study of plants and embryozem soils on the technogenic dumps aimed to the improvement of the monitoring and remediation in industrial zones

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Abstract. In the soil cover of technogenic territories (Usolye-Sibirskoye, Irkutsk Region, Eastern Siberia, Russia) the initial, organo-accumulative, soddy, and humus-accumulative embryozems were identified. The period of soil formation was established: from 20 years (organo-accumulative) to 40 years (humus-accumulative embryozems). The relationship between regenerative successions of vegetation and stages of the soil-forming process was found. Each stage of post-technogenic soil formation (type of embryozem) corresponds to a certain type of plant communities possessing a clear discrepancy in the species composition. The first stage is represented by plant communities comprising few ruderal species on the initial embryozem. The more advanced stage is characterized by complex communities consisting of grasses, shrubs, and trees on the humus-accumulative soil. It has been shown that the humus content determines the degree of natural restoration of biocenotic functions in the post-technogenic ecosystem. Plants-concentrators that can be effectively used in phytoextraction of metals for decontamination of embryozems have been studied. Natural renewal of vegetation and the development of soil-forming processes serve as the best option for the rational use of nature management in comparison with the artificial restoration of natural landscapes in technogenic territories.

1. Introduction
When industrial production wastes are stored at landfills, significant areas of land are formed, occupied by technogenic dumps and tailings [1]. The pollutants concentrated in the technogenic zone, sharply change the natural state of the environment of the adjacent areas, which is primarily manifested in the violation of the ecological functioning of vegetation and soil – the key habitat-forming components of the ecosystem [2]. In recent decades, when studying anthropogenic ecosystems, much attention has been paid to the restorative successions of phytocenoses [3, 4]. Such researches allow solving not only important ecological problems but also acquire practical value for the creation of steady homeostatic ecosystems [5, 6]. The formation of phytocenoses is one of the main integral criteria of restoration of natural functions of territories transformed during technogenesis [7]. Evaluation of syngenetic successions of vegetation makes it possible to characterize changes in the state of stability of emerging phytocenoses and the direction of the soil-forming process [8]. In this regard, technogenic dumps are representative models for studying vegetation successions, since the formation of technogenic soils begins from the zero point of ecosystem development [9]. According to the State report “State of energy conservation and energy efficiency in the Russian
Federation” (2017), more than 65% of the solid industrial waste of the Irkutsk region is stored in landfills, forming technogenic dumps [10]. In Usolye-Sibirskoye alone, the industrial dumps cover more than 350 hectares. As a result, there is a high risk of environmental pollution, disturbance of natural landscapes, the transformation of the functioning of natural ecosystems, up to complete destruction of plant communities, and depletion of land resources in the vast areas of limited land use. To restore natural ecosystems lost under the influence of various factors, the state regulatory documents provide for measures for their reclamation, protection, and rational use [11]. At present, studying the spatial and temporal dynamics of regenerative successions on the surface of technogenic soils is an urgent ecological task whose solution allows optimizing the phytoremediation of disturbed lands and carrying out optimal measures for their reclamation [12]. This circumstance determined the relevance of the research, which is to study the regularities of post-technogenic restoration of natural vegetation and soils on industrial territories to solve the problems of rational nature management.

It is known that so far in Russia and abroad no unified approaches to the integrated assessment of technogenic polygons as ecological systems have been developed [13]. In this aspect, an important direction of research, which determined the purpose of our investigation, is the study of the state of soils and plants on such polygons under intensive anthropogenic impact. The main tasks, which were solved within the present research: ecological characterization of the soil cover and plants of technogenic dumps; evaluation of the processes of biogeochemical migration of heavy metals (HMs) on the technogenic territory; studying the dynamics of vegetation succession and post-technogenic restoration of the territory; providing ecological recommendations for the reconstruction of territories.

2. Materials and Methods
The study was conducted in July 2020 within the industrial dumps of the large chemical production of the city of Usolye-Sibirskoye (Irkutsk region). Geobotanical relevés were performed on the sample plots (SP). Four test sites were selected, located in the radial direction at a distance of 1.5, 2.5, 3.5, and 5.5 km from the central part of the technogenic dump (52°47′07″ N, 103°34′59″ E). The state of trees and shrubs was investigated, and soil samples were taken by the profile method, the study of morphological and physical parameters of soils was carried [14, 15]. The morphological description of technogenic soils was carried out according to the classification of Androkhanov and Kurachev [4].

The content of chemical elements in soil and plant samples was determined by atomic absorption spectrophotometry, flame photometry, and photocolorimetry using the equipment of the Baikal Analytical Centre of the Irkutsk Scientific Centre of the Siberian Branch of the Russian Academy of Sciences. The total content of chemical elements in leaves and needles of plants was established after the preliminary ashing of samples in a muffle furnace. The mobile forms of elements were extracted from soils with 1M hydrochloric acid solution [14]. Technogenic impact on the soil was determined by calculating the total pollution index (Zc) of chemical elements [16]. Soil CO₂ emissions rate was determined by the adsorption method directly in the field [15]. The essence of the method lies in the determination of CO₂ on the soil surface by an absorber (alkali solution) followed by titration with acid. Algae samples were collected in sterile paper bags or glassware. For the morphology of the species, we used the material fixed in formaldehyde and dried. To identify plant species microscopes Axio Observer Z1 and Axio Scope A1 were used. The moisture content of the near-surface air layer was studied using a DS 1923 hygrochron and an iButton receiver of the DS1402DDR8 type (BlueDot).

Samples of grey forest soil and needles/leaves of trees and shrubs were taken from the 3 sites representing background territories: 52°11′02″ N, 103°15′21″ E; 52°47′17″ N, 102°59′42″ E; 52°07′18″ N, 105°16′40″ E. Forests possessing undisturbed soil cover and remote from the industrial zone of the city of Usolye-Sibirskoye on 80-150 km were typical for those areas. The background values for soils and plants correspond to the average values of the indicators of all surveyed areas.
3. Results and Discussion
The technogenic dumps of Usolye-Sibirskoye were formed by the storage of solid industrial waste. The studies have shown that in the industrial zone of Usolye-Sibirskoye there is an active development of embryozems [17]. According to our data, the process of embryozems formation in this zone proceeds over several decades (from 20 to 40 years). If in the initial soils – profile R1–R2 (their share is less than 5% of the total area of the dumps), any organogenic horizons are completely absent, then in the organo-accumulative soils – profile O–R1–R2 (their share is 20%), there is already an organic litter, in the soddy soils – O–AY–BER–BR–R, there is a well-formed soddy horizon (their share is 45%), in the humus-accumulative soils – O–AR–BER–BR–R (their share is 30%) there is a pronounced humus layer. According to our data, for soils of 40 years, more than 3 cm of humus horizon was formed (figure 1) and there was a change in the morphological structuring of the soil profile to a depth of more than 0.5-0.8 m. The large elastic technogenic substrate gradually decreased in size during the weathering process. At the same time, as the soil-forming process developed, mechanisms associated with the accumulation of humic matter and nutrients were formed in the embryozems [18, 19]. A significant accumulation of organic matter in humus-accumulative embryozem was found in the technogenic territory (figure 2). Embryozem soils, especially at the initial stage, have high water permeability by their physical properties, but their bare surface is subjected to drying and wind erosion. As a result, these soils formed on the artificial substrate have a high absorption capacity and rapid evaporation from the surface. Determination of natural field moisture capacity shows that volumetric moisture content in the upper (0-20 cm) layers of initial embryozem is 6-9%, organo-accumulative soils – 16-18%, soddy, and humus-accumulative ones – 24-26%, and 32-35% respectively. Daily registration of moisture content using in situ moisture loggers was also carried out. Significant differences (from 13 to 18%) are observed in the afternoon and the evening hours, while the greatest moisture loss is characteristic of the initial embryozem, and the least moisture loss is registered in the humus-accumulative embryozem. During a day, the relative humidity of the near-surface air layer of the initial embryozem decreases sharply, from 97 to 81% of the Relative Humidity ($RH$), while in the humus-accumulative it decreases slightly, from 97 to 94% $RH$. 

![Figure 1. Thickness of the humus-accumulative horizon of the embryozem, formed over 40 years.](image1)

![Figure 2. Accumulation of organic matter on the surface of soil aggregates of embryozem.](image2)
Intensive biochemical processes are being observed in the upper horizons of organo-accumulative, soddy, and humus-accumulative embryozems, which characterize the initial stage of humus matter development and soil transformation [20]. This is confirmed when studying the content of total carbon, total nitrogen, the C/N ratio in the upper horizons, and the CO₂ emission from the soil surface. Thus, in organo-accumulative embryozem (horizon AR), low content of total carbon from 0.3 to 0.5%, total nitrogen – 0.025 to 0.05% occurred, consisting of the C/N ratio 12 and 10 units. However, these parameters indicate favourable conditions for the formation of humus matter at the initial stage of soil formation. In soddy and humus-accumulative embryozem, a greater increase in the content of total carbon and nitrogen by 15-40%, a decrease in the C/N ratio by 2-3 units, and a decrease in CO₂ emissions to 10-20 mg/10g/day, respectively, are found. Such values indicate increased mineralization of organic matter and the formation of more stable humus matters.

It was expected that such harsh conditions (low moisture and nutrient content in the surface soil layer) will impede microorganisms to be involved in the initial stage of soil formation. However, microscopic examination of samples taken from the initial embryozem revealed massive development of cyanoprokaryotes in the cultures. Small-celled diatom algae and a representative of the Eustigmatales, *Vischeria helvetica* (Visch. et Pasch.) Hibb. were also abundant. In total, 11 species of terrestrial algae were identified. *Nostoc commune* Vaucher ex Bornet et Flahault forms macroscopic colonies on the technogenic soil surface in the study area (figure 3). The colonies of the species are unevenly distributed, they are particularly confined to spots where vegetation cover is absent, thinned, or in the litter next to vascular plants. It was revealed that the biomass of the *Nostoc commune* increases sufficiently on the soil surface with a thinned grass cover. The ability of *Nostoc commune* to form biomass on the surface of embryozems depleted in nitrogen and carbon indirectly indicates its essential role in the processes of soil and vegetation recovery.

![Figure 3. Macrocolonies of Nostoc commune on the surface of organo-accumulative embryozem.](image)

Studies have established that each type of embryozems corresponds to the distribution of certain plant communities. On the initial embryozem, the vegetation is represented by sparse pioneer groups of ruderal species. Ruderals, cereals, and sedges, small clumps of shrubs (*Padus avium* Miller, *Hippophae rhamnoides* L., *Salix viminalis* L.), and single low, strongly depressed trees of *Pinus sylvestris* L., *Betula pendula* Roth, and *Populus laurifolia* Ledeb. are occurred in small numbers on organo-accumulative embryozems. On soddy embryozems, the projective coverage increases, more than 10 species prevail. Where humus-accumulating embryozems are formed, the grass layer varies in coverage from 30 to 50% and includes about 15-20 species.

High concentrations of many chemical elements in the embryozems were found. The total pollution index $Z_c$ for the initial embryozem is 143.2; for organo-accumulative – 107.8; for soddy – 75.8; for humus-accumulative one – 65.4. At the same time, concentration coefficients (CC) of hazard classes HMs 1–3 in the organo-accumulative embryozem (the first stage of the soil formation process) reaches...
very high values: Sr 25.3 Th 14.7 Mo 13.7 Se 12.2 As 8.1 Cu 6.5 Pb 6.3 Cr 5.8 Cd 5.2 Zn 4.8 Ni 3.2 and the level of their pollution is characterized as extremely dangerous. In soddy and humus-accumulative embryozems the content of HMs in the soil profile is much lower, the level of contamination – dangerous. All technogenic soils are characterized by high alkalinity of the upper horizons, for the initial embryozem pH-water is 11-13, for organo-accumul ative soil is 10-12, and humus-accumulative one is 8-9. It was found that the progressing humus-forming process is observed in the industrial zone of the city of Usolye-Sibirskoye.

The method of accumulative phytoindication allowed us to determine the accumulation of HMs in the organs of herbaceous plants, trees, and shrubs. Plant species widely represented in anthropogenic zones were chosen as phytoindicators. During chemical-analytical studies of above-ground (stems, leaves, flowers) and underground (roots) biomass of herbaceous plants for HMs content, the main species-concentrators were identified: Melilotus albus Medikus, M. officinalis (L.) Pall., Trifolium hybridum L., T. repens L., T. pratense L., Vicia cracca L., Medicago sativa L., Sonchus arvensis L., Chamerion angustifolium (L.) Scop. The maximum values CC of HMs relative to the background were found in the above-ground biomass of plants growing on organo-accumulative embryozems. For these areas, CCs of HMs in plant stems are as follows: Sr 18.6 Th 11.2 Mo 9.8 Se 8.1 Cu 6.4 Cr 5.3 Zn 5.1 Ni 4.9 Pb 4.5 Cd 4.6, in roots – Sr 15.2 Th 9.2 Mo 7.3 Se 6.5 Cu 5.1 Cr 4.4 As 4.0 Ni 3.8 Zn 3.5 Pb 2.9 Cd 2.1.

A significantly high level of HMs content in pine needles, leaves of trees and shrubs, was also revealed. The highest concentrations of the elements are recorded in those industrial areas of Usolye-Sibirskoye, where organo-accumulative embryozems are formed. Unlike that, in the assimilative organs of plants on soddy and humus-accumulative embryozems, the concentrations of pollutant elements are significantly lower. It has been found that trees of different species growing on the most developed humus-accumulative embryozems can accumulate in the leaf phytomass the HMs concentrations exceeding the background level by 3.2-18 times. It was found that studied tree species are selective bioindicators to a particular HM or group of HMs. The highest concentrations of HMs were detected in the assimilative organs of the following species: Betula pendula Roth, Pinus sylvestris L., Salix viminalis L. Accordingly, these trees can be considered the best plant-concentrators of elements-toxicants. It should also be noted that all the trees and shrubs selected for the study are well adapted to harsh soil conditions, which allows their use for reclamation activities when restoring vegetation and soils in disturbed areas. The study revealed close ratios (r = 0.75-0.87) between the content of mobile forms of HMs in the lower horizons of embryozems and their gross content in the assimilative organs of trees. This is explained by the fact that in the lower horizons of embryozems significant concentrations of HMs are contained in the form of easily soluble salts and can be easily absorbed by the root system of trees. At the same time, the least correlations between HMs content in organo-mineral horizons and assimilative organs of trees were established for the most developed humus-accumulative embryozems.

4. Conclusion

The results obtained indicate that in the industrial zone of the city of Usolye-Sibirskoye the post-technogenic formation of vegetation cover and restoration of soil formation processes are observed. The main indicators of soil conditions can be listed as follows: the content of organic matter, the thickness of humus horizon, and acid-alkaline properties. These indicators of soils to a greater extent determine its protective capacity to multi-elemental pollution with HMs. Currently, the horizons of technogenic soils are found to contain significant amounts of HMs: Sr, Th, Mo, Se, As, Cu, Cr, Zn, Ni, Pb, Cd. Each stage of anthropogenic soil formation is accompanied by certain plant communities. The formation of the humus-accumulative embryozems and plant communities on the dumps will be the fundamental factors indicating the restoration of anthropogenic areas. To the remediation in industrial zones, one of the options is the formation of a bulk fertile (humus) layer in accordance with applicable environmental regulations on the surface of technogenic soils. In addition, facilitating the indigenous species settling down the disturbed areas, and the creation of artificial plant communities consisting of concentrator plants (herbaceous plants) will also contribute to the improvement of restoration of disturbed territories.
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