

## CHAPTER 5

### PHYTOGEOCHEMICAL CHARACTERISTICS OF TECHNOGENESIS SITES IN DONBASS: INDICATION AND PROSPECT OF REMEDIATION

**Andrei I. Safonov**  <https://orcid.org/0000-0002-9701-8711><sup>1</sup>

**Denis N. Dogadkin**  <https://orcid.org/0000-0002-6207-0130><sup>2</sup>

<sup>1</sup>Donetsk State University, Donetsk, Russia, e-mail: andrey\_safonov@mail.ru

<sup>2</sup>Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, Moscow, e-mail: denisnd@mail.ru

---

*In this paper, the elemental analysis of typical plants forming a stable association in the landscaping areas of the Donbass slag heaps was carried out. Initial geobotanical descriptions and botanical-toxicological experiments were carried out for seven slag heaps (Donetsk and Makeevka cities) to identify typical plant communities and their state under technogenic load on colliery waste dumps. In the 52-element composition of plant samples, pairwise correlations and co-pollution groups were determined in the migration activity of toxic compounds in plant tissues. Statistical accounting of concentration capacity indices of soil plants was carried out to identify the highest concentrations, which are considered as toxic in the phytprobe. It was found that colliery waste dumps in the state of 50-60 years of plant overgrowth (succession) is a chronic threat of increasing geochemical contrast in the region and directly in urban residential areas. The assumption that the remote and indirect effect of military events in Donbass may contribute additional geochemical contamination in the spoil heaps of central cities has not been confirmed. The morphological plasticity of plants and forms of teratogenesis of vegetative and generative organs were considered as indicator effects of specific contaminations on spoil heaps. The analysis of the most stable plant populations in anthropogenic objects and information on the peculiarities of elemental composition in geosystems is the basis for plant selection and effective use in phytoremediation of disturbed ecotopes. The conducted experiment is unique for the territory of the Central Donbass*

*(2014-2024) to identify biogeochemical characteristics in open landscape systems of anthropogenic origin.*

**Keywords:** *biogeochemistry, coal mine dumps, Donbass, phytoremediation, industrial pollution, phytoindication, terricon, technogenesis, ecological monitoring.*

---

## INTRODUCTION

The system of creating slag heaps (and gob piles, depending on the morphology of the landscape formation) in Donbass is an inevitable consequence of the industrial development of the region (Gamov et al., 2016). Underground coal mining has been practiced in this area for more than 150 years. There are more than 20 metallurgical and 60 chemical production facilities of various purposes. On the one hand, there is a mechanical transformation of the landscape (Abramowicz & Rahmonov, 2024; Kříbek et al., 2018; Massante, 2015) with the formation of more than 800 slag heaps as products of mining activities. On the other hand, slag heaps are a source of air and groundwater pollution (Dai et al., 2022; Kříbek et al., 2020; Li et al., 2023; Peña-Ortega et al., 2019 ) as a result of combustion processes and emission of a large number of decomposition products of complex technogenic nature (Boorboori & Lackóová, 2023; Jiang et al., 2024; Kolesnikov et al., 2019). At the same time the whole industrialization is the cause of natural environment pollution as a result of coke-chemical, metallurgical and many variations of implementation of chemical technologies (Ermakov & Jovanovic, 2010; Ermakov et al., 2016; Jianina, 2023; Linnik, 2018; Strizhenok & Ivanov, 2021; Yeprintsev et al., 2020). Therefore, comprehensive studying of the current state of technogenic objects (Bezel' et al., 2020; Ermakov et al., 2020; Ivaneev et al., 2023; Rahmonov et al., 2024; Yeprintsev et al., 2013; Zhuykova et al., 2022) embedded in the landscape system of large cities and residential complexes is relevant.

Botanists of Donetsk region since 1960s (at formation of Donetsk Scientific Center of Academy of Sciences and reorientation of Pedagogical University into classical Donetsk State University) have always had an acute objective of phytooptimization of disturbed and polluted natural ecosystems as a result of anthopotechnogenesis, that is why the work on landscaping and landscape architecture was actively developed during the USSR period. The first stages of slag heap reclamation were particularly complex and toxic - it was a landscape transformation of colliery waste dumps in such a way that conditions were created for the survival of pioneer

plants, which later form the environment for more productive plant communities. Until the mid-1980s, the landscaping program was successful, much was accomplished. But the lack of government support thereafter gave a sharp decline in the effectiveness of such landscaping on a large scale. For the last 40 years the character of vegetation formation on slag heaps can be called self-overgrowing (Grakhova et al., 2020; Massante, 2015; Rouhani et al., 2023) - a very slow successional process (Li et al., 2023; Pereira et al., 2024; Tabunshchik et al., 2020; Ukraintseva et al., 2014) of open areas sodding in landscapes of technogenic nature.

There are more than 300 slag heaps on the territory of Donetsk and Makeevka alone, which are essentially coal industry wastes, but some scientists consider them as a resource of the future (Heiskanen et al., 2022; Kříbek et al., 2018; Tien et al., 2022) with rich deposits of valuable ores, rare earth elements (Dai et al., 2022; Jianina, 2023; Kříbek et al., 2020; Li et al., 2023) and so on. However, these programs are not being developed today due to military actions.

Modern green revolution and new generation evolution also require expert assessment of the resource potential of the territory (Belogurov, 2024; Kharchenko et al., 2021; Mirnenko, 2024; Neamtu et al., 2021; Nekhoroshkov et al., 2022). This should involve specialists in the field of geosystem modeling (Belogurov, 2024; Boyarshinov et al., 2022; Nugroho & Surendro, 2024; Vasin, 2018; Yepintsev et al., 2023; Zhgun, 2020; Zhong et al., 2023), analytical chemists (Korobova et al., 2023; Lavrinenko et al., 2021; Świsłowski et al., 2022), geochemists (Ermakov, 1995, 2017; Jovanović & Ermakov, 2020), technologists (Frunze, 2023; Maslennikov, 2021; Soldatova et al., 2021), soil scientists (Kolesnikov et al., 2019, 2022; Maslennikov, 2021; Zheng et al., 2024), biologists of a wide training profile (Bezel' et al., 2020; Blinkova et al., 2023; Korniyenko & Kalaev, 2022; Kozlova et al., 2022; Opekunova, 2016), and environmental specialists in the field of anthropogenic load rationing (Heiskanen et al., 2022; Kolesnikov et al., 2019; Manzhilevskaya et al., 2022; Pogányova et al., 2019).

In topical aspect, the development of high-precision technologies in Donbass is temporally abandoned due to active military actions. Realization of any experiment in open landscape systems is not only harmful, but also dangerous for the mentioned reason. There are problems to organize an ecological expedition of diagnostic purpose, there is a ban on the organization of photography in any places: in populated areas, protected sites and especially in places of technogenesis, as any such information can be used for the purposeful destruction of the region's infrastructure. Soil sampling is prohibited, including for the safety of

researchers. Therefore, from 2014 to the present, there are no detailed ecological monitoring programs at the state level with accessible publications. The only exception is the phytomonitoring system in the Central Donbass, which unites 113 stationary and observation posts of transient importance (Avraimova & Safonov, 2023; Nespirnyi & Safonov, 2024; Safonov, Alemasova, Zinikovskaia et al., 2023; Zinikovskaia, Safonov et al., 2024). The system is based on the use of data on the state of indicator plants (Glukhov & Safonov, 2024; Safonov, 2016, 2023; Zinikovskaia, Vergel, Safonov et al., 2023). It should be said that, despite the difficulties and dangers, the scientific staff of the Department of Botany and Ecology of Donetsk State University, graduate students and undergraduates all these years are selflessly involved in the implementation of phytomonitoring based on indication, which is reflected in some topical publications in different aspects (Alemasova & Safonov, 2022; Dogadkin, Safonov et al., 2024; Frunze, 2023; Kharchenko, Kalaev, Kornienko, 2021; Korniyenko & Kalaev, 2022; Mirnenko, 2024; Safonov, 2022; Safonov, Dogadkin, Nespirnyi, 2024; Zinikovskaia, Safonov, Yushin, Nespirnyi, Germonova, 2024).

Since 2023, on the initiative of the Chief Researcher of Vernadsky Institute of Geochemistry and Analytical Chemistry, Doctor of Biological Sciences, Professor Vadim Viktorovich Ermakov, the work on biogeochemical analysis of natural environments of Central Donbass was started (Dogadkin, Safonov, Danilova, Degtyarev, 2024; Safonov, Dogadkin, Nespirnyi, 2024).

The purpose of this work is to introduce the results of primary screening on detailed elemental composition of plants from stable populations on slag heaps in Donbass for their geochemical assessment and in the future use for restoration of disturbed and polluted ecosystems.

## **CONDITIONS, OBJECT AND METHODOLOGY OF THE EXPERIMENT**

The experiment was based on the principles of monitoring research in urbanized or highly industrialized regions (Yeprintsev et al., 2013, 2020, 2023). When selecting sites (slag heaps) for sampling, we were guided by available historical references on their creation and geostrategic representativeness of their location (Gamov et al, 2016). The unspoken objective was also to expand the monitoring network and to determine the possibility of the influence of military events on the biogeochemical contrast indicators in the city limits of Donetsk and Makeevka as the most densely populated points of the Donetsk economic region. Therefore, the

applied ideology of site selection and territorial preferences is conditioned by additional expertise in search of possible geochemical anomalies, apparently having negative consequences for the health of local residents.

The botanical-ecological aspect of the experiment is based on the search for a plant association adequate to the request, unified for all biomaterial collection points and obtaining representative collection with subsequent chemical analysis of samples (Abramowicz & Rahmonov, 2024; Bezel' et al., 2020; Ermakov, 2004; Zheng, 2024). In practice, it has been established that the most sustainable are the northeastern exposures of colliery waste dumps, as in summer time high insolation on the southern and western parts of the slope level out the possibility of productive development of biota in a natural way. The publications of leading specialists in this field (Ermakov, 2017; Ermakov et al., 2018; Grakhova et al., 2020; Jovanović & Ermakov, 2020; Kolesnikov et al., 2019; Korobova et al., 2023, Kovalskij, 1977; Kříbek, 2018; Opekunova, 2016; Rahmonov et al., 2024; Tien et al., 2022; Zhuykova et al., 2022) are valuable recommendations in sampling for biogeochemical experiment. Among the theoretically expected results, it was important to confirm the presence of migration flows of elements and to consider the concentration abilities of dominant plants forming stable vegetation cover in the technogenesis zones.

For analytical control in a series of slag heap experiments X Series II inductively coupled plasma quadrupole mass spectrometer (ICP-MS) by Thermo Scientific equipped with a concentric atomizer and a quartz cyclone atomization chamber cooled by a Peltier element (2°C) was used. The calibration dependences of the elements were determined using standard reference solution 68 Element Standards ICP-MS-68A (Solution A and Solution B) from High-Purity Standards, North Charleston, SC, USA.

Some results of chemical analysis using the atomic absorption method were also used, including for retrospective evaluation of available results, and to expand the possibility of correct data interpretation.

The geostrategic part of the experiment was carried out according to the available topical screens of botanical-ecological GIS survey. Objects of *Poaceae* and *Asteraceae* families were selected for material collection. Test sites on landfills Donetsk & Makeevka: 1) at the Kalinin terricon mines (48°01'23"N; 37°50'53"E); 2) Zaperevalnaya (47°59'45"N; 37°52'49"E); 3) Berestovskaya No. 6/14, Ganzovka, Horned terricon (48°02'13"N; 37°52'09"E); 4) No. 1-1 bis (48°01'42"N; 37°50'28"E); 5) Tsentralno-Zavodskaya terricon mines (47°59'16"N; 37°48'52"E); 6) Gorky

(47°59'47"N; 37°47'03"E); 7) St. Serafimovskaya (48°02'14"N; 37°50'37"E).

The work is part of research activities within the framework of the scientific heritage of V.I. Vernadsky on the concentration function of living matter (Vernadsky, 1940, 1980), V.V. Kovalsky (Ermakov & Kovalsky, 1974; Kovalskij, 1977) and A.P. Vinogradov (Ermakov, 2017; Vinogradov, 1938) in the field of biogeochemistry. In the modern aspect, the ideology of the experiment is based on the developments of V.V. Ermakov and co-authors (Ermakov, 2004, 2012, 2015, 2017; Jovanović at al., 2020, 2023; Ermakov at al., 1995, 2010, 2012, 2016, 2018, 2020, 2021). The initial experimental data were processed using various data analysis methods (data validation, correlation analysis, cluster analysis, principal component analysis) are presented in the discussion of the obtained patterns. We also used the methods of statistical processing of information reasonable for the specificity of experiments and tested earlier for local Donbass ecosystems.

## RESULTS AND DISCUSSION

The dominant role of *Phleum pratense* in plant associations on the northeastern exposures of slag heaps was established. Representatives of *Poaceae* in a number of tolerant species occupy the leading position when analyzing promising species for the necessary phytoremediation technology in the conditions of anthropogenic impact on the natural environment. At the same time, in practice, the property of stability is more important, and the characteristic of accumulation of toxic elements and their compounds is secondary in importance. Without the first property, the existence of species is impossible, and due to the second characteristic there is an involvement of elements in biogeochemical processes and protection of especially toxic compounds from direct exposure to the human body, for instance, with dust.

Representatives of the cereal family are universal ground cover plants, as they form a protective layer on toxic substrates, which vegetates for 10 months of the year, and in winter continues to form a protective horizon as part of a dense herbaceous vegetation cover.

Among the species that are assectators during the first to third decade of September in 2023, the following were identified: *Plantago lanceolata* L., *Elytrigia stipifolia* (Czern.) Nevski at the Kalinin terricon mines (48°01'23"N; 37°50'53"E), *Astragalus cicer* L., *Trifolium campestre* Schreb. - Zaperevalnaya (47°59'45"N; 37°52'49"E), *Echium vulgare* L., *Picris hieracioides* L. - Beerestovskaya No. 6/14, Ganzovka, Horned

terricon (48°02'13" N; 37°52'09"E), *Verbascum lychnitis* L., *Trifolium pratense* L. - terricon mines No. 1-1 bis (48°01'42"N; 37°50'28"E), *Oenothera biennis* f. *stenopetala* (E.P. Bicknell) B.Boivin - Tsentralno-Zavodskaya (47°59'16"N; 37°48'52"E), *Cirsium vulgare* (Savi) Ten. - Gorky (47°59'47"N; 37°47'03"E), *Setaria verticillata* (L.) P.Beauv - St. Serafimovskaya (48°02'14"N; 37°50'37"E). The conditions under which monoid thickets of *Phleum pratense* are formed were the basis for selecting the aboveground vegetative mass of this species and conducting an ingredient analysis.

In Fig. 1 there is an image of a landfill (top view) and, for an illustrative example, photographs of monodominant plant associations are provided. The projective coverage ranges from 98 to 100%. The selection of plant material was carried out by the envelope method in five repetitions, however, two photographs are provided for a contrasting comparison of the condition of plants at the foot of the landfill (Fig. 1, a) and at the place of the greater impact of technogenesis - in the middle part of the slope of the coal mine dump (Fig. 1, b).

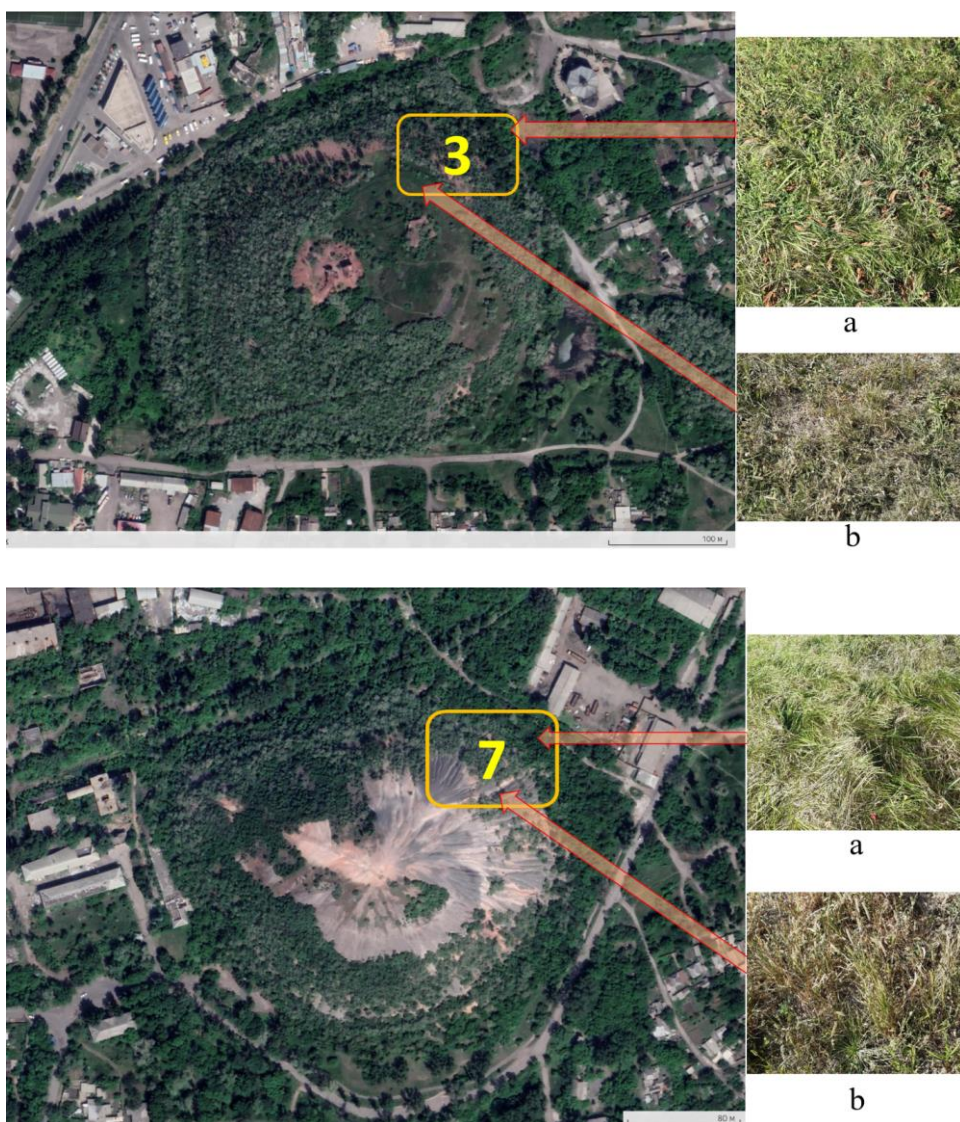


*Figure 1. Detailed sampling of plants at registration sites No. 3 & 7 (as an illustrative example) at the foot of the landfill (a) and in the middle of the rise (b)*

For each chemical element, we consider the values of its concentration at each waste heap as a specific sample. The most important order statistics (minimum, maximum and all quartiles including median value) and some other measures are calculated for each sample. Boxplots are provided for some elements. The choice for detailed visualization of these data is due to

the different ranges of concentration variation. Results are presented in the form of boxplots (Fig. 2).

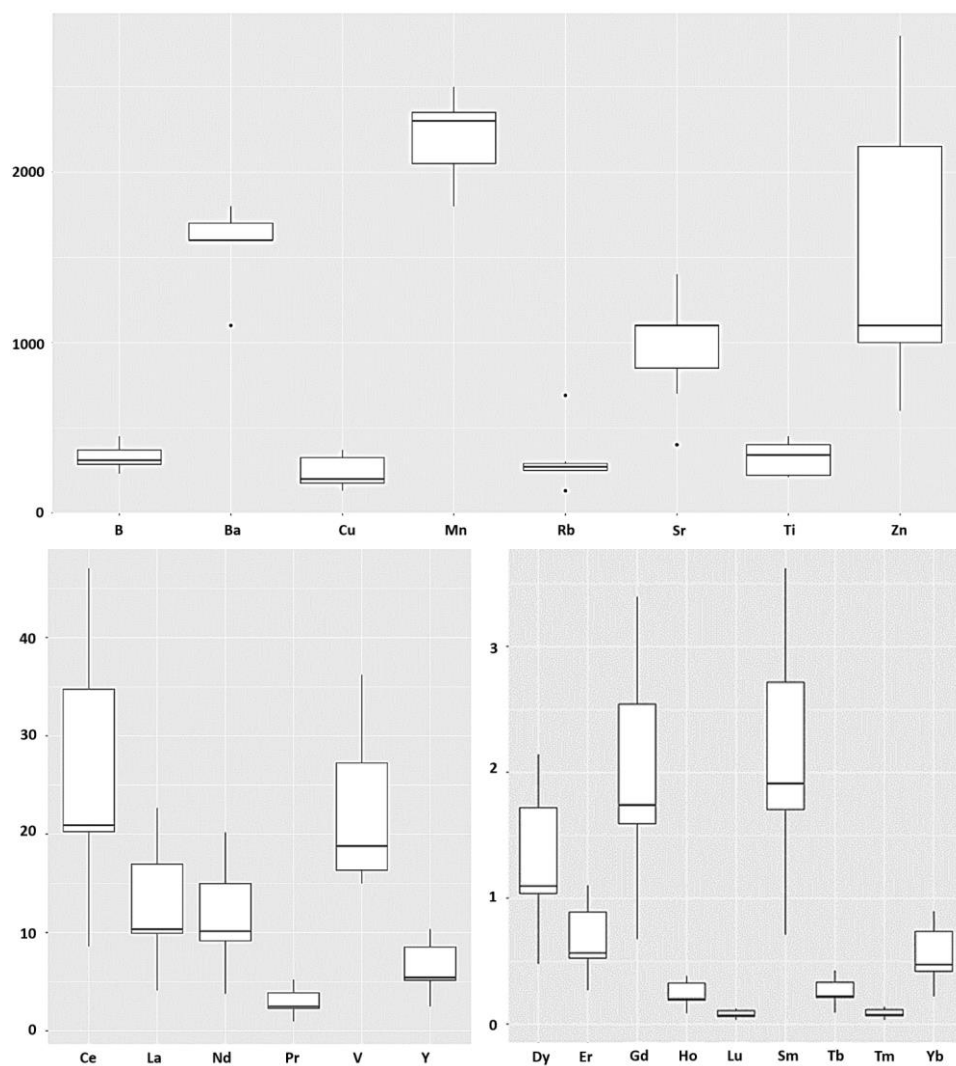


Figure 2. Features of accumulation of some chemical elements in the tissues of the experimental plant *Phleum pratense* L.

The specificity of ranking elements in the mineral part of phytosamples (using the example of samples of the vegetative part of the dominant *Phleum pratense* in associations) at the Tsentralno-Zavodskaya terricon mines is reflected in the following series of concentrations: Zn (2800) >

Mn (2300) > Ba (1600) > Sr (1100) > Ti (420) > B (350) > Cu (330) > Rb (300) > Li (60,9) > Mo (52,1) > Cr (51,8) > Ce (47,1) > Pb (44,4) > Ni (41,8) > V (36,2) > La (22,7) > Nd (20,2) > Sc (14,7) > Y (10,4) > Zr (9,6) > Co (8,1) > Nb (7,9) > Se (5,7) > Ga (5,4) > Pr (5,22) > Sm (3,62) > Gd (3,39) > Th (3) > As (2,4) > Ge (2,2) > Cs (2,17) > Dy (2,14) > Cd (2) > Sb (1,76) > W (1,68) > U (1,6) > Er (1,1) > Be (0,9) > Yb (0,89) > Sn (0,5) > Eu (0,49) > Tl (0,44) > Tb (0,43) > Ho (0,38) = Bi (0,38) > Hf (0,27) > Tm (0,14) > Lu (0,12) > Re (0,11) > Te (0,09) > Ta (0,05) > Hg (0,01).

In comparison with the features of accumulation in plants of the waste heap of the Kalinin mine (Safonov, Dogadkin, Nespirnyi, 2024), the waste heap of the Tsentralno-Zavodskaya mine is the most saturated with technophile elements: zinc, cobalt, molybdenum, as well as a group of lanthanides, which also have the nature of pollution as a result of the metallurgical industry and heavy industry for the production of alloys and equipment.

The results of the ingredient analysis (Fig. 3) make it possible to identify an individual geochemical profile and establish background characteristics of elemental composition for mining sites.

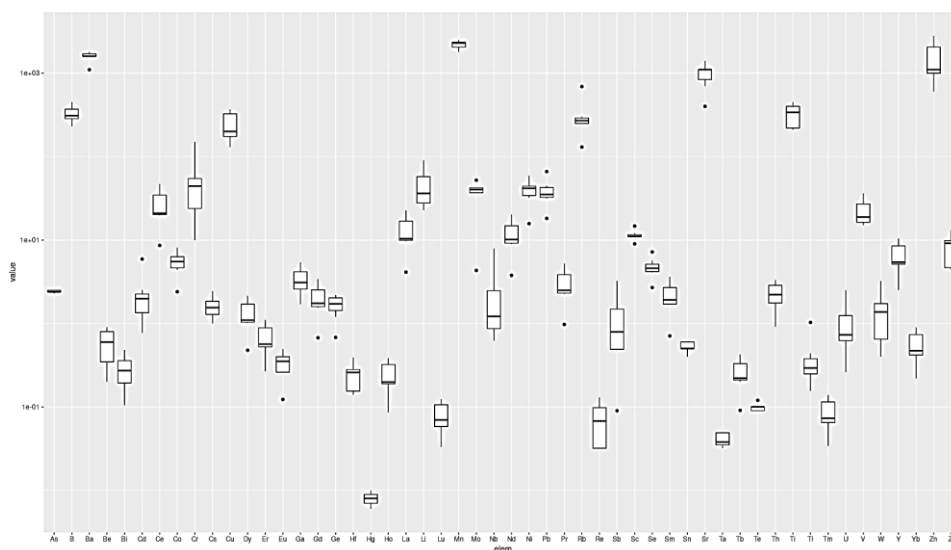
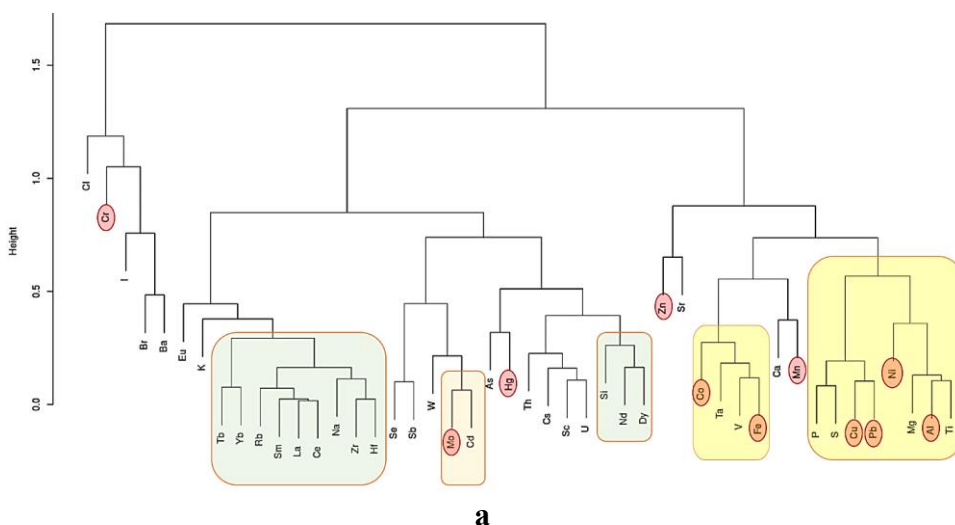


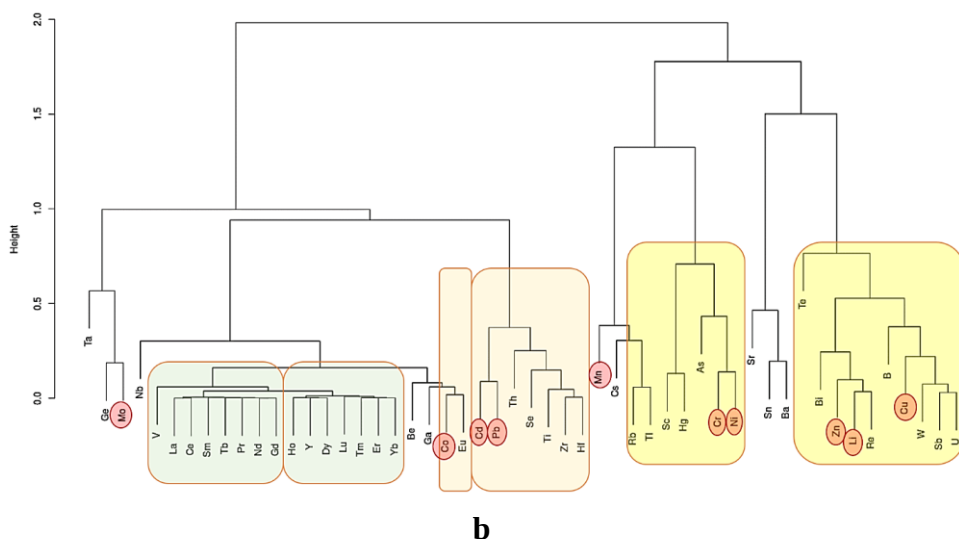
*Figure 3. Features of the accumulation of elements in the test plant*

Taking into account the fact that the scales of the values are incommensurable (from the order of 0.01 for Hg to the order of 1000 for Mn, Zn, Sr, Ba), a logarithmic scale is used on the vertical axis. Horizontally, the elements are arranged alphabetically (Fig. 3).

Cluster dendrograms (Fig. 4) give the most accurate visual representation of the structure of all links between elements: their joint input into the plant organism and the accumulation character. Certainly, the specificity of interactions in migration flows of substances when compared with background air pollution (by concentration of elements in mosses) and in soil (by accumulation in stable communities of cereals), have characteristic differences. Thus, it is possible to differentiate in determining the geochemical specificity of objects of different economic use, for instance, in places of increased technogenic impact and on the territory of protected sites.

For the convenience of information perception (Fig. 4), some metal groups are combined in a separate color. Particularly interesting and specifically technophilic elements are highlighted in red (Fig. 4). It has been established that such elements can be conjugated in migration flows with others, for example, cadmium, lead, cobalt, nickel, molybdenum, and also have their own separate scenario of entry into the plant organism, for example, zinc in the bodies of mosses and arsenic in the tissues of cereal plants-remediants.





**b**

*Figure 4. Cluster dendrograms of the elemental composition of the phytogeochemical background and contrast in Donbass by the moss method of neutron activation analysis (citation by Ziniovskaya I., Safonov A., Yushin N., Nesporny V., Germonova E. (2024) with additions) - (a) and by bluegrass plants on landfills by inductively coupled plasma mass spectrometry (citation by Safonov A., Dogadkin D., Nesporny V. (2024) with additions) - (b)*

The specifics of the geochemical profile for different landfills of Donbass: the Zaperevalnaya mine's landfill priority pollutants included in biogeochemical cycles are Cu, Zn, W, Cd, and U; terricon mines No. 6/14 Berestovskaya - Mn, Rb, and Tl; terricon mines No. 1-1 bis - Cs; terricon mines Tsentralno-Zavodskaya - Co, Zn, Y, Nd, Mo, La, Ce, Nd, Sm, and Dy; terricon mines Gorky - Zr, Cd, Pb, and Th; terricon mines St. Serafimovskaya - Cr and Ni (in the system of comparing the data obtained for seven objects of man-made origin).

The closest relationship has been established in the groups of co-accumulation of elements: lanthanides, Zr-Hf, Cu, Li-Re-(Zn), Rb-Tl, Cd-Pb, Sc-Hg, Cr-Ni, Sb-U-(W-Cu). However, given the small size of the initial sample, such patterns should be further studied during repeated sampling in order to confirm or refute the indicated trends.

In the works (Nesporny & Safonov, 2024; Safonov, Dogadkin, Nesporny, 2024; Ziniovskaya, Safonov, Yushin, Nesporny, Germonova, 2024), the principal component method was successfully used to analyze data on the ingredient composition of mosses and higher flowering plants

in Donbass. In these papers, the most informative linear combinations of normalized concentrations of various chemical elements on the waste heaps are identified.

It is not possible to obtain historical information about the sources of the rock during the formation of a specific landfill in the Donetsk People's Republic during the period of hostilities, therefore, for comparative analysis, the method of phytogeochemical monitoring at the present stage remains the only technology for the indirect identification of technogenesis processes in Donbass.

Since the studied natural and anthropogenic complexes are not part of the food program and migration flows in the technozems - plant organism system are not involved in a controlled system of agricultural technologies, it does not seem advisable to consider the issues from the point of view of compliance of the data obtained for individual elements according to maximum permissible concentrations. However, the process of involving particularly toxic elements from an aggressive environment into plant organisms is certainly important in analyzing the effectiveness of phytoremediation and reclamation works, which should be part of the ongoing methods of optimizing and restoring the disturbed balance in ecosystems.

Taking into account the general high mineralization, including toxic components of natural environments in Donbass, the priority conclusion of the causes of teratogenicity is precisely the excess, and not the lack of any element or group of elements of the technophilic series of pollution.

A fundamentally important objective was to establish possible transformations of the geochemical status of the studied slag heaps in connection with the military events in Donbass. In Figure 5, the places of field stress and impact of military events are marked by an additional red areola and its displacement in the direction of pointers. The indicator metal for plants of the group of higher flowering plants on the impact of toxic explosion factors is zinc. For this purpose, we conducted a specific comparative experiment of zinc migration fluxes in indicator plants on slag heaps. Apparently, the level of most toxic elements on slag heaps was already initially high (in Donetsk and Makeevka), moreover, samples for chemical analysis were collected outside the areas of direct impact of explosions to ensure the purity of the experiment in field conditions.

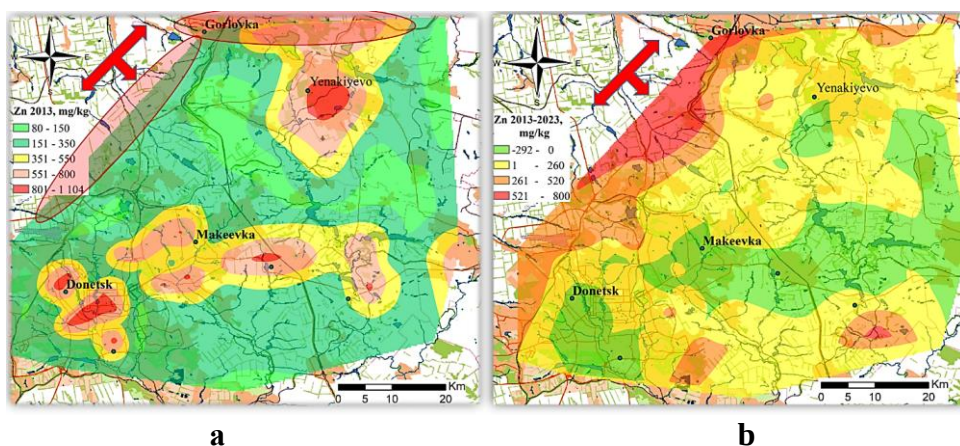


*Figure 5. Cartographic methods of data visualization for the Central Donbass by indicator element (zinc) (a) in connection with the conduct of military operations in the dynamics of 2013-2023 (b) (citation by Zinicovskaia I., Safonov A., Yushin N.S., Nespirnyi V.N., Germonova E.A. (2024) with additions)*

It has been established that, as of 2013, the geochemical features of Zn migration flows in indicator phytosystems (Fig. 5, a) are characterized by its compact distribution in terms of gravity to industrial facilities and places of central urbanization. Whereas in dynamics over 10 years by 2023 (Fig. 5, b) at least two geochemical provinces were identified in the southern regions of the 2018-2019 total screening monitoring network (15-22 km<sup>2</sup> each) and one province in the northwest with a total area of more than 70 km<sup>2</sup>.

It was found that over a 10-year observation period (with data for 11 growing seasons for plant organisms recorded), the area of the territory with a decrease in toxic concentrations of Zn of presumably man-made origin is more than 370 km<sup>2</sup>. Judging by the fact that this trend is stable for urban agglomerations of such large metallurgical centers as Donetsk, Makeyevka and Yenakiyevo (Fig. 5), the summary part of the experiment concludes that pronounced stagnation processes in the metallurgical industry of the region over the years of the experiment.

However, considering that the accumulation of Zn in plant objects is also associated with many stressful periods, including natural climatic induction and the factor of war, it is also assumed that high accumulations of this element as protective mechanisms of adaptive nature, which is consistent with the data of publications by other authors (Fernández-Braña et al., 2023; Grakhova et al., 2020; Kolesnikov et al., 2019; Lottermoser,

2007; Sidenko et al., 2001). The cumulative effect of Zn in indicator plants revealed in the experiment may be endogenous in nature, since it provides complex geochemical stability of plants.

It was found that colliery waste dumps in the state of 50-60 years of plant overgrowth (succession) is a chronic threat of increasing geochemical contrast in the region and directly in urban residential areas. The assumption that the remote and indirect effect of military events in Donbass may contribute additional geochemical contamination in the spoil heaps of central cities has not been confirmed.

The conducted experiment is unique for the territory of the Central Donbass (2014-2024) to identify biogeochemical characteristics in open landscape systems of anthropogenic origin.

The conducted experiment is considered as a primary analysis of data on phytogeochemical features of slag heaps in Donbass. Thanks to these data, groups of chemical elements united by joint migration and accumulation processes in the plant organism featured by a high level of tolerance to the existing growing conditions and forming monospecific thickets were identified, which was important for the implementation of reliable experiment.

## **CONCLUSION**

The slag heaps of Donbass, considered on model examples, by biogeochemical (as the initial link of migration - phytochemical) characteristics are an integral part of anthropogenically transformed landscape. Colliery waste dumps have a specific ingredient composition (established for 52 chemical elements), forming prerequisites for toxic impact on the natural environment.

To establish the phytogeochemical profile of each slag heap and to carry out a comparative analysis between them becomes possible in accordance with the principles of botanical and ecological monitoring, the use of modern method of chemical-analytical control (mass spectrometry with inductively coupled plasma) and different ways of statistical processing of data allowing to visualize. The specificity of interactions as a joint accumulation of individual elements in general for the mining industry and different methods of statistical data processing, making it possible to visualize the specifics and patterns of interactions of both the joint accumulation of particular elements in general for mining, and territorial differences in the analysis of this process.

From the point of view of botanical and toxicological expertise, the following groups of elements are of the greatest interest for subsequent

geochemical surveys in places of influence of landfills on the environment: La-Ce-Sm-Tb-Pr-Nd-Gd and Ho-Y-Dy-Lu-Tm-Er-Yb, Li-Re-(Zn), Sb-U-(W-Cu), Cd-Pb, Co-Eu, Zr-Hf, Rb-Tl, Zr-Hf, Sc-Hg, Cr-Ni. Upon detailed study, this indicates the presence of potential geochemical anomalies in man-made landscapes and requires repeated analytical control.

The vegetation horizon and its successful developmental characteristics are a powerful barrier to the penetration and free migration in the environment of new toxic compounds produced by anthropotechnogenesis. The elements themselves are in many cases not considered harmful to the development of living organisms, but their high concentrations are the cause of toxic effects. It is proved by accumulative ability of plants, which in practice have properties to form a dense vegetation cover on places of high mineralization and mechanical transformation. The plant species used in this work are recommended for wide implementation for restoration works in disturbed ecosystems both as a result of urbanization, industrialization and in conditions of conducting hostilities. In this case, both pioneer communities of soil algae, mosses and flowering plants with cover-ground architectonics are important.

## ACKNOWLEDGMENT

The authors express their sincere gratitude to *Vadim V. Ermakov*, Professor, Doctor of Biological Sciences, a leading researcher of Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences (Moscow), for his help in developing the ideology of the experiment and initiating relevant biogeochemical developments in Donbass; founder of the autonomous non-governmental organization «Center Nousystem» (Moscow), member of the Russian Geographical Society *Anton Yu. Khlynov* for facilitating experiments and successful transportation of samples for analysis; researcher at Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences *Valentina N. Danilova* for preparing plant samples for analysis; Associate Professor of Donetsk National Technical University *Ekaterina A. Germonova* for her long-term assistance in GIS analysis of the obtained botanical material; student Donetsk State University, researcher at Donetsk Galkin Institute of Physics and Technology *Roman A. Safonov* for assistance in sampling and developing a safe route during the implementation of the primary part of the experiment. The authors would like to thank *Vitalii Nesporny* (Economic Research Institute, Donetsk) for his help in mathematical (statistical) processing of the material.

The task has been completed within the framework of the youth laboratory «Diagnostics and mechanisms of adaptation of natural and anthropogenically transformed ecosystems of Donbass» (№ 1023110700153-4-1.6.19;1.6.11;1.6.12).

Part of this work performed at the Vernadsky Institute of Geochemistry and Analytical Chemistry was supported by the Ministry of Science and Higher Education of the Russian Federation, within the budget theme of the Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences.

Completed within the framework of the work of the Azov-Black Sea Mathematical Center (Agreement No. 075-02-2024-1446).

## REFERENCES

1. Abramowicz, A.K., Rahmonov, O. (2024). Element cycling at thermally active coal-waste dumps: a case study of *Calamagrostis epigejos* and *Solidago Canadensis*. *Resources*, 13(6), p. 73. DOI: 10.3390/resources13060073
2. Alemasova, A.S., Safonov, A.I. (2022). Heavy metals in phytosubstrates as indicators of anthropogenic air pollution in industrial region. *Lesnoy vestnik / Forestry Bulletin*, 26(6), 5-13. DOI: 10.18698/2542-1468-2022-6-5-13
3. Avraimova, T.V., Safonov, A.I. (2023). Ecological developments in Donbass: Bibliographic control and promotion of research. *Scientific and Technical Libraries*, 3, 30-42. DOI:10.33186/1027-3689-2023-3-30-42
4. Belogurov, V. (2024). Generalized assessment of region environmental state based on mathematico-cartographic modeling with GIS. *Industrial Technologies and Engineering (ICITE 2023)*. Vol. 474. *Les Ulis*, 02001. DOI: 10.1051/e3sconf/202447402001
5. Bezel', V.S., Zhuikova, T.V., Gordeeva, V.A., Goloushkina, E.V. (2020). Biogeochemistry of impact regions: the role of edaphic and phytocoenotic environmental factors. *Geochemistry International*, 58(10), 1135-1144. DOI:10.1134/S0016702920100043
6. Blinkova, O., Rawlik, K., Jagodziński, A.M. (2023). The impact of environmental factors on traits of *Hedera helix* L. vegetative shoots. *Plant Ecology*, 224(11), 973-986. DOI: 10.1007/s11258-023-01354-w
7. Boorboori, M.R., Lackóová, L. (2023). Biochar; an effective factor in improving phytoremediation of metal(iod)s in polluted sites.

- Frontiers in Environmental Science, Vol. 11.  
DOI:10.3389/fenvs.2023.1253144
8. Boyarshinov, G.S., Popov, A.B., Odintsova, A.A., Gvozdk, S.A., Rybkina, A.I., Korolkova, A.A. (2022). Application of Geoportal's Web-Technologies in GIS, Case Study: Interactive Geology Atlas. Russian Journal of Earth Sciences, 22(3), ES3002.  
DOI:10.2205/2022ES000794
  9. Dai, L., Wang, L., Wan, X. (2022). Potentially toxic elements exposure biomonitoring in the elderly around the largest poly-metallic rare earth ore mining and smelting area in China. Science of the Total Environment, Vol. 853, 158635.  
DOI:10.1016/j.scitotenv.2022.158635
  10. Dogadkin, D., Safonov, A., Danilova, V., Degtyarev, A. (2024). Biogeochemical monitoring of terricones of Central Donbass, screening of 2023. International Scientific Conference «Green economy and adaptation of industry to climate changes». 22-24 April 2024. Beograd: Naučno-stručno društvo za zaštitu životne sredine Srbije Ecologica. (Zemun: Akademska izdanja). p. 52.
  11. Ermakov, V., Safonov, V., Dogadkin, D. (2021). Characteristic features of molybdenum, copper, tungsten and rhenium accumulation in the environment. Innovative Infrastructure Solutions, 6(2). DOI: 10.1007/s41062-021-00481-5
  12. Ermakov, V.V. (1995). Biogeochemical provinces: concept, classification and ecological estimation. Geochemistry International, 33(5), 150-165.
  13. Ermakov, V.V. (2004). Technogenesis and biogeochemical evolution of taxons in the biosphere. Ecologica (Beograd), 9(41), 3-12.
  14. Ermakov, V.V. (2012). Evolution of biogeochemical provinces in Russia. In: Changing the natural environment in the XX century. (Rds. V.M. Korlyakov and D.Yu. Lyuri), Moscow, Mplnet. 404 p.
  15. Ermakov, V.V. (2015). Geochemical Ecology and Biogeochemical Criteria for Estimating the Ecologic State of Biospheric Taxons. Geochemistry International, 53(3), 195-212.  
DOI:10.1134/S0016702915030064
  16. Ermakov, V.V. (2017). A.P. Vinogradov's concept of biogeochemical provinces and its development. Geochemistry International, 55(10), 872-886. DOI: 10.1134/S0016702917100044
  17. Ermakov, V.V., Jovanovic, L.N. (2010). Biodiversity and the biosphere technogenesis. Ecologica (Belgrad), 17(58), 77-85.
  18. Ermakov, V.V., Jovanovic, L.N. (2012). Innovative methods of biogeochemical indication. Ecologica, 19(66), 93-98.

19. Ermakov, V.V., Korobova, E.M., Degtyarev, A.P., Tyutikov, S.F., Karpova, E.A., Petrunina, N.S. (2016). Impact of natural and manmade factors on migration of heavy metals in the Ardon River basin (North Ossetia). *J. Soils Sediments*, 16(4), 1253-1266. DOI:10.1007/s11368-015-1247-7
20. Ermakov, V.V., Kovalsky, V.V. (1974). *Biological significance of selenium*. Moscow, Nauka, 298 p.
21. Ermakov, V.V., Tyutikov, S.F., Danilova, V.N. (2020). Ecological monitoring of the Unal Depression, Northern Ossetiya-Alania, using techniques of biogeochemical indication. *Geochemistry International*, 58(3), 332-341. DOI: 10.1134/S0016702920030040
22. Ermakov, V.V., Tyutikov, S.F., Safonov, V.A. (2018). *Biogeochemical indication of microelementoses*. Moscow: Publ. Russian Academy of Sciences. 486 p. (In Russian)  
<https://www.elibrary.ru/item.asp?id=36404273>
23. Fernández-Braña, A., Salgado, L., Gallego, J.L.R., Afif, E., Boente, C., Forján, R. (2023). Phytoremediation potential depends on the degree of soil pollution: a case study in an urban brownfield, *Environmental Science and Pollution Research*, 30(25), 67708-67719. DOI: 10.1007/s11356-023-26968-5
24. Frunze, O. (2023). Sorption capacity of ornamental herbaceous plants under conditions of soil contamination with lead. *E3S Web of Conf.* Vol. 462. 02004. DOI: 10.1051/e3sconf/202346202004
25. Gamov, M.I., Levchenko, S.V., Rylov, V.G. (2016). Metal-containing coals of the East Donetsk Basin: regularities of formation and integrated-use prospects. *Russian Geology and Geophysics*, 57(8), 1161-1170. DOI: 10.1016/j.rgg.2016.08.004
26. Glukhov, A.Z., Safonov, A.I. (2024). Phytomonitoring concept for anthropogenically disturbed regions. *Scientific research of the SCO countries: synergy and integration: Proceedings of the International Conference, Beijing*, pp. 96-104.  
DOI:10.34660/INF.2024.87.72.160
27. Grakhova, S.P., Olenchenko, V.V., Yurkevich, N.V. (2020). Comparison of geophysical and geochemical parameters of the Belovo zinc facility dumps (Kemerovo Region) in the Process of Recultivation. *IOP Conference Series: Earth and Environmental Science*, 459(3), Chapter 2, 032050. DOI:10.1088/1755-1315/459/3/032050
28. Heiskanen, J., Ruhanen, H., Hagner, M. (2022). Effects of compost, biochar and ash mixed in till soil cover of mine tailings on plant growth and bioaccumulation of elements: A growing test in a

- greenhouse. *Heliyon*, 8(2), e08838.  
DOI:10.1016/j.heliyon.2022.e08838
29. Ivaneev, A.I., Brzhezinskiy, A.S., Karandashev, V.K. (2023). Assessment of sources, environmental, ecological, and health risks of potentially toxic elements in urban dust of Moscow megacity, Russia. *Chemosphere*, Vol. 321, 138142.  
DOI:10.1016/j.chemosphere.2023.138142
  30. Jiang, Ch., Wang, Ya., Chen, Y., Wang, Sh., Mu, Ch., Shi, X. (2024), The phytoremediation potential of 14 *Salix* clones grown in Pb/Zn and Cu mine tailings. *Forests*, 15(2), 257.  
DOI:10.3390/f15020257
  31. Jianina, F. (2023). Environmental governance: challenges of environmentally friendly industrial areas in Dhaka city of Bangladesh. *International Journal Papier Advance and Scientific Review*, 4, 19-25. DOI: 10.47667/ijpasr.v4i4.260
  32. Jovanović, L.N., Ermakov, V.V. (2020). The importance of selenium and zinc in the prevention and treatment of viral diseases. *Ecologica*, 27(99), 357-365.
  33. Jovanović, L., Ermakov, V.V., Ostroumov, S.A. (2023). The role of green economy transition in green growth and environmental protection. 2nd International thematic monograph. Academic editions, Belgrade, Serbia, 277 p.
  34. Kharchenko, N.N., Kalaev, V.N., Kornienko, V.O. (2021). Mechanical resistance of *Quercus robur* L. at the environmental boundary of the species distribution in the steppe. *IOP Conference Series: Earth and Environmental Science*, 12049.  
DOI:10.1088/1755-1315/875/1/012049
  35. Kolesnikov, S.I., Kuzina, A.A., Minnikova, T.V., Ter-misakyants, T.A., Nevedomaya, E.N., Akimenko, Yu.V., Trufanov, D.A., Kazeev, K.Sh., Burachevskaya, M.V., Minkina, T.M., Shende, S.S., Barakhov, A.V. (2022). Biodiagnostics of resistance to the copper (Cu) pollution of forest soils at the dry and humid subtropics in the greater Caucasus Region. *Forests*, 13(10), 1720. DOI: 10.3390/f13101720
  36. Kolesnikov, S.I., Zubkov, D.A., Zharkova, M.G., Kazeev, K.Sh., Akimenko, Yu.V. (2019), Influence of oil and lead contamination of ordinary chernozem on growth and development of spring barley. *Russian Agricultural Sciences*, 45(1), 57-60.  
DOI:10.3103/S1068367419010075
  37. Korniyenko V.O., Kalaev V.N. (2022) Impact of natural climate factors on mechanical stability and failure rate in silver birch trees

- in the city of Donetsk // Contemporary Problems of Ecology. Vol. 15, No 7. P. 806-816. DOI: 10.1134/s1995425522070150
38. Korobova, E.M., Baranchukov, V.S., Kolmykova, L.I. (2023). Theoretical and methodological approaches to the analysis of the spatial distribution of endemic diseases of geochemical nature. *Geochemistry International*, 61(10), 1074-1086. DOI:10.1134/s0016702923100063
  39. Kovalskij, V.V. (1977). *Geochemische Okologie / Biogeochemie*. Berlin: VEB Deutscher Landwirtschaftsverlag. 355 s.
  40. Kozlova, E.A., Orlova, E.E., Zubik, I.N., Simakhin, M.V. (2022). Growth and development analysis of silver Bryum (*Bryum argentum* Hedw.) depending on illumination level influence. *IOP Conference Series: Earth and Environmental Science*, IOP Publishing. 042012. DOI: 10.1088/1755-1315/981/4/042012
  41. Kříbek B., Knésl I., Majer V., Sracek O., Mihaljevič M. (2018) Geochemistry and environmental impact of neutral drainage from an uraniferous coal waste heap. *Journal of Geochemical Exploration*, 191, 1-21. DOI: 10.1016/j.gexplo.2018.05.001
  42. Kříbek, B., Míková, J., Knésl, I., Mihaljevič, M., Sýkorová, I. (2020). Uptake of trace elements and isotope fractionation of Cu and Zn by birch (*Betula pendula*) growing on mineralized coal waste pile. *Applied Geochemistry*, Vol. 122, 104741. DOI:10.1016/j.apgeochem.2020.104741
  43. Lavrinenko, Y., Plieva, A., Zinicovscaia, I., Hristozova, G., Frontasyeva, M., Tkachenko, K., Dogadkin, D., Gromyak, I., Kolotov V. (2021). Elemental composition of infusions of herbs (Tisanes) of north Ossetia (the Caucasus). *Agriculture*, 11(9), DOI: 10.3390/agriculture11090841
  44. Li, D., Jiang, C., Jiang, C., Liu, F., Zhu, Q. (2023). Geochemical characteristics and migration patterns of rare earth elements in coal mining subsidence lakes under the influence of multiple factors. *Science of the Total Environment*, Vol. 904, 166668. DOI:10.1016/j.scitotenv.2023.166668
  45. Linnik, V.G. (2018). *Landscape differentiation of technogenic radionuclides*. Moscow: RAS. 372 p.
  46. Lottermoser, B.G. (2007). *Mine Wastes (Second Edition): Characterization, treatment, environmental impacts*. 1-304 p. DOI: 10.1007/978-3-540-48630-5
  47. Manzhilevskaya, S., Petrenko, L., Kravchenko, S., Mytsyk, V., Pnev, A. (2022). Green roof as ecological security design solution

- during reconstruction of buildings. Conference INTERAGRO-MASH 2021. Precision Agriculture and Agricultural Machinery Industry, Volume 2: Conference proceedings: Springer, 2022. pp. 235-245. DOI: 10.1007/978-3-030-80946-1\_24
48. Maslennikov, P.V. (2021), Geoecological features of zinc accumulation in the soil-plants system of urban ecosystems. *Journal of Sustainability Science and Management*, 16(4), 21-36. DOI:10.46754/JSSM.2021.06.003
  49. Massante, J.C. (2015). Mining disaster: restore habitats now. *Nature*, 528(39). DOI: 10.1038/528039c
  50. Mirnenko, E. (2024). Ecological monitoring of water bodies: Bioindication, microalgae biodiversity indices. *E3S Web Conf.*, Vol. 555, 02008. DOI: 10.1051/e3sconf/202455502008
  51. Neamtu, R., Sluser, B., Plavan, O., Teodosiu, C. (2021). Environmental monitoring and impact assessment of Prut River cross-border pollution. *Environmental Monitoring and Assessment*. 193 (6). DOI: 10.1007/s10661-021-09110-1
  52. Nekhoroshkov, P., Peshkova, A., Ziniovsciaia, I., Vergel, K., Kravtsova, A. (2022). Assessment of the atmospheric deposition of heavy metals and other elements in the mountain Crimea using moss biomonitoring technique. *Atmosphere*, 13(4), 573. DOI: 10.3390/atmos13040573
  53. Nespirnyi, V., Safonov, A. (2024). The importance of principal component analysis for environmental biodiagnostics of Donbass. *E3S Web Conf.*, 555, 01007. DOI:10.1051/e3sconf/202455501007
  54. Nugroho, H.A., Surendro, K. (2024). Comprehensive bibliometric analysis of missing value imputation. *IEEE Access*. 12, 14819-14846. DOI: 10.1109/access.2024.3357533
  55. Opekunova, M.G. (2016). Bioindication of pollution: studies stipend. 2nd ed. Publisher: St. Petersburg: Publishing House of St. Petersburg University, 300 p.
  56. Peña-Ortega, M., Valencia-Sauceda, J., de la O-Villanueva, M., Del Rio-Salas, R., Méndivil-Quijada, H., Minjarez-Osorio, C., Molina-Freaner, F., Moreno-Rodríguez, V. (2019). Environmental assessment and historic erosion calculation of abandoned mine tailings from a semi-arid zone of northwestern Mexico: insights from geochemistry and unmanned aerial vehicles. *Environmental Science and Pollution Research*, 26(25), 26203-26215. DOI: 10.1007/s11356-019-05849-w
  57. Pereira, P., Ferreira, C.S.S., Zhao, W. (2024). Editorial: Nature-based solutions for ecosystem restoration. *Current Opinion in*

- Environmental Science and Health, 39, 100546.  
DOI:10.1016/j.coesh.2024.100546
58. Pogányova, A., Mičieta, K., Dušička, J. (2019). Genotoxic assessment of selected native plants to differentially exposed urban ecosystems. *Environmental Science and Pollution Research*, 26 (9), 9055-9064. DOI: 10.1007/s11356-019-04230-1
  59. Rahmonov, O., Kowal, A., Rahmonov, M., Pytel, S. (2024). Variability of concentrations of potentially toxic metals in the topsoil of urban forest parks (Southern Poland). *Forests*, 15(6), 1020. DOI:10.3390/f15061020
  60. Rouhani, A., Skousen, J., Tack, F.M.G. (2023). An overview of soil pollution and remediation strategies in coal mining regions. *Minerals*, 13(8), 1064. DOI: 10.3390/min13081064
  61. Safonov, A. (2023). Indicator plants of anthropogenic disturbances: Scientific approach, educational technologies. *E3S Web of Conferences*. EDP Sciences, 01031. DOI: 10.1051/e3sconf/202343101031
  62. Safonov, A.I. (2016). Phytoindicational monitoring in Donetsk. *World Ecology Journal*, 6(4), 59-71.
  63. Safonov, A.I. (2022). Abnormalities of embryo structures in Donbass indicator plants. *Diversity of plant world*, 3(14), 5-18. DOI: 10.22281/2686-9713-2022-3-5-18
  64. Safonov, A.I., Alemasova, A.S., Zinikovskaia, I.I., Vergel, K.N., Yushin, N.S., Kravtsova, A.V., Chaligava, O. (2023). Morphogenetic abnormalities of bryobionts in geochemically contrasting conditions of Donbass. *Geochemistry International*, 61(10), 1036-1047. DOI: 10.1134/s0016702923100117
  65. Safonov, A.I., Dogadkin, D.N., Nespirnyi, V.N. (2024). Phyto-geochemical features of some coal mine dumps in the Donbass. *Bulletin of Donetsk National University. Series A: Natural Sciences*. No 3, 80-94. (in Russian).
  66. Sidenko, N.V., Bortnikova, S.B., Pal'chik, N.A., Gieré, R., Cottard, F. (2001). Mobility of heavy metals in self-burning waste heaps of the zinc smelting plant in Belovo (Kemerovo Region, Russia). *Journal of Geochemical Exploration*, 74(1-3), 109-125. DOI: 10.1016/S0375-6742(01)00178-9
  67. Soldatova, E., Gromyak, I., Dogadkin, D., Dong, Y., Li, J., Sun, Z., Ivanova, I., Toropov, A. (2021). Geochemical conditions of natural wetland and paddy fields in the Poyang Lake area, China. *SN Applied Sciences*, 3(1). DOI: 10.1007/s42452-020-04060-8

68. Strizhenok, A.V., Ivanov, A.V. (2021). Monitoring of air pollution in the area affected by the storage of primary oil refining waste. *Journal of Ecological Engineering*, 22(1), 60-67. DOI:10.12911/22998993/128873
69. Świsłowski, P., Vergel, K., Zinicovscaia, I., Rajfur, M., Waclawek, M. (2022). Mosses as a biomonitor to identify elements released into the air as a result of car workshop activities. *Ecological Indicators*, 138, 108849. DOI: 10.1016/j.ecolind.2022.108849
70. Tabunshchik, V.A., Kluchkina, A.A., Petlukova, E.A., Kalinchyk, I.V., Galkina, M.V., Penno, M.V., Nikiforova, A.A. (2020). Assessment of the geomorphological basis of landscapes of the Crimean Peninsula using geoinformation technologies. *IOP Conference Series: Materials Science and Engineering*. 012066. DOI: 10.1088/1757-899X/905/1/012066
71. Tien, D.P.T., Van Dung, D., My, T.T.T., Frontasyeva, M., Zinicovscaia, I., Khiem, L.H., Son, N.A. (2022). Studying airborne trace elements in featured areas in Red River Delta and South Central Vietnam using moss biomonitoring technique and neutron activation analysis. *Journal of Radioanalytical and Nuclear Chemistry*. DOI: 10.1007/s10967-022-08331-z
72. Ukraintseva, N., Leibman, M., Mikhaylova, T., Streletskaya, I. (2014). Geochemistry of plant-soil-permafrost system on landslide-affected slopes, Yamal, Russia as an indicator of landslide age. *Environmental Science and Engineering (Subseries: Environmental Science)*, 107-131. DOI: 10.1007/978-3-319-00867-7\_9
73. Vasin, Y. (2018). Models, methods and information technologies for creating, processing and analyzing spatially distributed data in GIS. *RPC 2018 - Proceedings of the 3rd Russian-Pacific Conference on Computer Technology and Applications*. 8482196. DOI: 10.1109/RPC.2018.8482196
74. Vernadsky, V.I. (1940). *Biogeochemical sketches 1922-1932*. Moscow-St.Petersburg: Publishing house of the USSR AS. 250 p. (in Russian).
75. Vernadsky, V.I. (1980). *Problems of biogeochemistry (Proceedings of Biogeochem. lab.)*. Moscow: «Nauka», 290 p. (in Russian).
76. Vinogradov, A.P. (1938). *Biogeochemical provinces and endemics*. Report of the Academy of Science of the USSR, 18 (4-5), 283-286 (in Russian).
77. Yeprintsev, S., Kurolap, S., Klepikov, O., Shekoyan, S. (2020). Assessment of the impact of technogenic air pollution on the social

- processes of large urbanized regions. E3S Web of Conferences. 03009. DOI: 10.1051/e3sconf/202021503009
78. Yeprintsev, S., Kurolap, S., Klepikov, O., Vinogradov, P. (2023). Remote monitoring of factors determining the environmental safety of urban areas. E3S Web of Conferences, Vol. 389, EDP Sciences. 03030. DOI: 10.1051/e3sconf/202338903030.
  79. Yeprintsev, S.A., Kurolap, S. A., Komov, I. V., Minnikov, I. V. Y. (2013), Monitoring of factors of ecological safety of urbanized territories' population (by example of settlements of Voronezh region). Life Science Journal, 10(12s), 846-848.
  80. Yeprintsev, S.A., Shekoyan, S.V., Lepeshkina, L.A. (2019). Technologies for creating geographic information resources for monitoring the socio-ecological conditions of cities. IOP Conference Series: Materials Science and Engineering. 012012. DOI: 10.1088/1757-899X/582/1/012012
  81. Zheng, X., Han, G., Song, Zh., Liang, B., Yang, X., Yu, Ch., Guan, D.X. (2024). Biogeochemical cycle and isotope fractionation of copper in plant-soil systems: a review. Reviews in Environmental Science and Biotechnology, 23(1), 21-41. DOI: 10.1007/s11157-024-09681-8
  82. Zhgun, T.V. (2020). Conditionality of the principal component method in the problem of calculating the composite index of a system from a series of observations. Journal of Physics: Conference Series. 012081. DOI: 10.1088/1742-6596/1658/1/012081
  83. Zhong, R., Liu, Sh., Li, H., Zhang, J. (2023). Sparse logistic functional principal component analysis for binary data. Statistics and Computing, 33(1), 15. DOI: 10.1007/s11222-022-10190-3
  84. Zhuykova, T.V., Meling, E.V., Bezel, V.S. (2022). Dynamics of alpha diversity during the restoration succession of grass communities of fallow lands and pits. Russian Journal of Ecology, 53(3), 158-168. DOI: 10.1134/S1067413622030134.
  85. Zinikovskaia, I., Safonov, A., Kravtsova, A., Chaligava, O., Germonova, E. (2024). Neutron activation analysis of rare earth elements (Sc, La, Ce, Nd, Sm, Eu, Tb, Dy, Yb) in the diagnosis of ecosystems of Donbass. Physics of Particles and Nuclei Letters, 21(2), 186-200. DOI: 10.1134/S1547477124020158.
  86. Zinikovskaia, I., Safonov, A., Yushin, N.S., Nespirnyi, V.N., Germonova, E.A. (2024). Ingredient phytomonitoring in Donbass for identifying new geochemical anomalies. Ecological Chemistry, 33(1), 19-32. EDN: DSDGFO (in Russian).

87. Zinikovskaia, I.I., Vergel, K.N., Safonov, A.I., Yushin, N.S., Kravtsova, A.V., Chaligava, O. (2023). Using moss *Ceratodon purpureus* (Hedw.) Brid for assessing the technogenic pollution (Ni, Zn, Mn, Al, Se, Cs, La, and Sm) of transformed ecotopes of Donbass. *Ecosystem Transformation*, 6(3), 22-38.  
DOI:10.23859/estr-220726