Remote sensing for environmental safety of forest ecosystems within the tailings impact of a closed tin ore company

L T Krupskaya¹,²,³ A M Orlov²,³ M B Bubnova³, M Y Filatova¹,² and
K A Kolobanov¹,²

¹Department of Ecology, Resource Use and Life Safety, Pacific National University,
136 Tichookeanskaya Street, Khabarovsk 680035, Russian Federation
²Department of Forest Protection and Forest Ecology, Far East Scientific Research Institute of Forestry,
71 Volochaevskaya Street, Khabarovsk 680030, Russian Federation
³Mining Institute FEB RAS, 51 Turgeneva Street, Khabarovsk 680000, Russian Federation

*Corresponding email: ecologiya2010@yandex.ru

Abstract. The article presents the results of the study of the problem of developing the scientific basis for ensuring the ecological safety of forest ecosystems using remote sensing of the Earth. We are talking about increasing the degree of their protection in the conditions of increasing the negative impact of pollution by waste from the processing of tin ores in the Vysokogorsky tailing dump of the closed Khrustalnensky GOK. Therefore, the aim of the study was to use methods of remote sensing of the impact on the forest ecosystems of the tailing dump to solve environmental problems. The article presents the principles of ensuring their environmental safety from waste, taking into account geoinformation technologies. The article presents an analysis of the current state of the tailing dump surface as a source of intensive technogenic pollution of forest ecosystems, and an assessment of the processes of evolution of environmental components after the termination of technogenic impact using remote sensing of the Earth. The use of remote sensing methods made it possible to clarify the migration routes and the nature of the flows of pollutants from the discarded tailing dumps. Ways to reduce their negative impact on forest ecosystems have been developed.

1. Introduction
Mineral resources development in Russia has increased scope, and in future, the georesources consumption will only grow. Intensive technogenic pollution, degradation and disappearance of natural resources, as well as a sharp deterioration of the human environment are taking place. Undoubtedly, mining production here is becoming increasingly resource-intensive. Economic reasons inevitably accompany it. However, the complexity of the problem lies in the fact that the whole system, regulating the technogenic impact of indicators, was formed on the basis of biological laws, and the possibility of compliance with existing sanitary and hygienic standards depends solely on the level of knowledge in technology [1]. In this regard, the natural biota can be preserved only by applying technologies with controlled exterior exposure. Determination of biological limits and technological possibilities is necessary. Therefore, the preservation or irreversible destruction of the mobile ecological balance in the environment depends on how mining production will be organized in the next half century, what restrictions and permits will be imposed on its development.
Here, the negative impact on the environment has already reached a level that exceeds the restorative nature powers [2-7]. Today, the world community is forced to solve the global problem of mining not disturbing the ecological balance in nature. This is evidenced by our analysis of literary data and patent search. For example, the article by B. Zhang et al [8] presents the results of a study on application of hyperspectral remote sensing for environmental monitoring in mining areas of Australia and China. Based on the analysis of biogeochemical action of dominant minerals, vegetation spectrum and vegetation indices, two hyperspectral indices were derived: Vegetation Inferiority Index (VII) and Water Absorption Disrelated Index (WDI). Experimental data show that VII can effectively distinguish between stressed and unstressed vegetation growth situations in mining areas. It has been shown that the VII sensitivity to vegetation growth conditions is superior to the traditional vegetation index – NDVI. Another index, WDI, can tell whether vegetation was affected by a particular mineral. The successful application of VII and WDI shows that hyperspectral remote sensing is an effective method for monitoring and vegetation assessment in mining areas.

The team of Millán García et al [9] proposed to monitor flood damage for vegetation from mining activities using optical remote sensing. The aim of the study was to determine the location of mine-related flooding. The proposed solution reduces monitoring costs for mining companies by identifying potential flooding zones.

Research by D Zhu et al [10] focused on the problem of monitoring the surface mining operations environmental impact using an environment remote sensing index. The authors found that use of MW-RSEI values provides valuable information on the environment around the quarry, which can be used for fast and effective monitoring of the environment changes in mining areas of China.

The study by Xu J et al [11] is of great interest, they established a method for classification of vegetation dynamics by remote sensing based on Landsat image time series using the example of open-cast mining in China. Experimental studies prove that the method proposed in the paper is not only simple, but also accurate and efficient. The authors believe that the integration of high-resolution remote sensing data and digital elevation models based on satellite data, such as Cartosat-1 and Cartosat-2 and Light Detection and Ranging (LiDAR), with land data has great potential in assessing and monitoring land degradation at the local scale. The application of remote sensing and GIS technologies for assessment and mapping physical, chemical and vegetation degradation is shown.

G P O Reddy [12] shows the possibilities of using remote sensing and GIS technologies for assessing and mapping physical, chemical and plant degradation.

In his article T Goswami et al [13] presents the results of a study on monitoring of technogenic air pollution in Singapore using GIS technology and remote sensing.

According to the research team of M Gül et al [14], the assessment of the mining environmental impact in Muğla Aydın (southwest Turkey) using Landsat and Google Earth imagery was made. The purpose of this study was to determine the geospatial changes of mining activities in Muğla-Aydın provinces in south-western Turkey. Landsat-5 TM, Landsat-7 ETM, Landsat-8 OLI and Google Earth satellite image data of 1984, 1994, 2004, 2014 and 2018 were used for change detection analysis. The study found that, taking into account the access roads to the quarries, factories and water storage dams, the technogenic impact extends over an area of 3 800 ha. There are several archaeological sites and endemic biota in the study area. Thus, there is an urgent need to relocate and protect archaeological heritage and endemic biota by special zones creation. It is concluded that the rich geomorphological features of the study area, which have been forming during millions of years, are endangered.

The article by V P Potapov et al [15] outlines a modern approach to environmental monitoring of mining regions using the Earth remote sensing methods and geoinformational technologies. The authors propose a new approach to the construction of environmental monitoring systems for mining areas, based on the integration of classical sampling methods, field studies and algorithms of remote sensing data processing. The scheme of system geportal construction is given. The advantages of such implementation over the traditional hosting location are shown. It should be noted that integration of classical methods of environmental research, remote sensing tools, as well as the latest achievements of geoinformation technologies allows creating modern environmental monitoring.
systems. They not simply allow to operate actual data, but also provide accumulation and deep analysis of information, as well as its accessibility and adaptation to a level of the end-user.

The paper by V P Potapov et al [16] considers the first in the Russian Federation prototype of an integrated information and computing system for dynamic assessment and prediction of the environmental state of the coal mining region, which provides collection and storage of data on natural resources monitoring. The developed system is the core of the environment quality management system not only for one enterprise separately, but for the coal mining area and the region as a whole. Assessment of ecological state of land, vegetation, water resources and atmospheric air and a forecast of atmospheric pollution and precipitation of atmospheric aerosols on the underlying surface is made due to integration and provision of information support of land-based and remote monitoring data. For the first time, the system solves the problem of real-time assessment of industrial aerosol dispersion and deposition due to mass explosions during coal mining. Data on meteorological parameters can come from the System of Measurement of Meteorological Parameters of Atmosphere SIMPA-2I (SMMPA-2M) both in the manual observation and in the automated modes, which allows achieving high accuracy of calculations of pollutant emission and distribution in the adjacent areas. The system is open and may be updated with new maps, databases and calculation models. In addition to the implemented models, the first priority may be given to the models of sound (or shock) wave propagation, watercourse pollutants and others. Access to environmental information on the activities of an individual coal mining enterprise or coal mining area is ensured not only for specialists of various environmental and technical services at various levels, but also for the general public, while the requirement for proprietary information non-disclosure is maintained.

O L Giniyatullina et al [16-17] considered the application of remote sensing data for geo-environmental monitoring of coal mining areas. An algorithm of a comprehensive environment survey using satellite imagery is presented. Practical application of remote monitoring to assess the coal mining impact on natural objects is shown by the example of the Kuzbass mining region. The authors state that modern technologies of the Earth remote sensing enable to conduct analysis and assessment of geo-ecological state of coal-mining regions as a whole. Application of remote sensing data enables to record the state of the territory almost immediately, with the same state of observation of all monitoring sites. This makes it possible promptly track and analyze the processes of environmental changes, to ensure regular observation, especially within the conditions of land-based observation data shortage. And the spectral reflectivity of objects allows identifying objects, determining the class of pollutants, occurrence reasons and also tracking insignificant changes in their state.

The study by Sh. G. A. Asmaryani [18] on the application of remote sensing technologies in ge-ecological research are of great practical interest. It outlines the basic scientific and technological resources for the development of promising areas, which will provide a reliable scientific and methodological foundation for the improvement and development of remote sensing methods and creation of monitoring system on this basis. The researchers believe that the combination of ground-based and space-based data, as well as an interdisciplinary approach in the study of the problem of providing a reliable scientific and methodological basis will improve remote sensing methods and create on this basis a monitoring system to address territorial management and sustainable development.

G V Shibalova [19] studied the possibilities of remote sensing application for collection information on disturbed lands. Up-to-date methods to obtain information for land state using space-based remote sensing systems have been considered. The characteristics of existing satellite scanning systems were given and conditions for remote sensing data reception and distribution were described. Methods and software tools of thematic interpretation and interpretation of multispectral remote sensing data were discussed using the example of erosion process monitoring tasks. The feasibility of ERS data application for development of erosion control measures was shown. The author concludes that the use of remote sensing data in the field of environmental management extends the possibilities of obtaining reliable information on disturbed lands used in the development of environmental protection measures and the design of engineering protection facilities.
The articles by V I Usikov et al [20] outline the results of an ecological assessment of the Komsomolsky mining district and the Jewish Autonomous Region (Russia) based on remote sensing data. Another paper by V I Usikov et al. [21] presents the results of remote sensing of natural-technogenic environment in the mining areas of the southern Far East Region.

I.V. Zenkov et al [22] presents the results of the assessment of the ecological state of lands disturbed during development of the Volchansky coal deposit in the Sverdlovsk Region. In the course of the research it was found that ecologically acceptable restoration of vegetation cover in the area of rock dumps was partly due to reclamation works, and mainly due to natural processes of its self-remediation. Studies using ERS information resources revealed highly effective restoration of the forest ecosystem. The authors show that these sites can be considered indicative from the position of ecological balance restoration in the area of land disturbed by open-cast coal mining. The work on the reclamation of rock dumps in general had a positive impact on their ecological state, as well as contributed to the shift of the eco-balance towards its improvement in the natural landscapes adjacent to the open-cast mining operations.

The analysis and generalization of domestic and foreign experience indicate that in the conditions of both operating and closed mining enterprises of the Far Eastern Federal District the named problem has not been studied enough. In this regard, the purpose of the study was to use remote sensing methods within the boundaries of the tailings dump impact of a closed tin ore enterprise to solve environment conservation problems.

2. Methods and Materials
Natural-mining technogenic systems formed as a result of tin ore mineral development were the object of the study. The problem was studied in 2012-2020 within the impact of tailings dump containing toxic highly sulphidized wastes of the closed mining enterprise Khrustalnensky GOK in the PrimorskyKrai (Territory). The methodological basis of the study was the doctrine of Academician V I Vernadsky about biosphere and noosphere [23] and the basic statements by B P Kolesnikov and L V Motorina stated in the Program and Methodology of Technogenic Biogeocenoses Study [24].

The present state of the mining area in the Primorsky Krai was analyzed by the example of the Kavalerovo tin ore district using different combinations of spectral channels of Landsat 8 satellite images and other Earth remote sensing (ERS) information resources.

To analyze phytomass growth in the study area, the Vega-Science tool for scientific analysis of satellite observation data developed at the Space Research Institute of the Russian Academy of Sciences [25] was applied. For this purpose, the sites within Vysokogorsky tailing dump were surveyed and the value of vegetation index NDVI [26] was calculated using the following formula:

\[
NDVI = \frac{(NIR - RED)}{(NIR + RED)}
\]

where, NIR - reflection in the near-infrared area of the spectrum, RED - reflection in the red area of the spectrum.

Analysis of snow cover samples, technogenic soil, plants, and industrial wastewater was performed on the ICP-MC Elan DRC II Perkin Elmer mass spectrometer (USA). Modern physico-chemical, chemical, biological methods, as well as mathematical modeling and GIS technology were used. The microflora was studied according to the methods of D G Zvyagintsev [27].

The results of the research were processed by generally accepted methods of variation statistics using PC software packages.

3. Results and Discussion
In the last century, the deposits in the Kavalerovsky tin ore district were mined by both open-pit and closed-pit methods by the Khrustalnensky GOK mining company. The Vysokogorsky concentrating plant was built to process the minerals. At present, about 23 million tons of toxic sulphidized mineral processing waste has been accumulated here, stored in the Vysokogorsky tailing dump, located on the 8 ha area. Hazard class is 2 (highly hazardous). The main ore mineral in the mineral composition of
the processing waste is cassiterite, which belongs to a group of minerals more resistant to oxidation, therefore sulphides are key elements in the process of hypergenesis zone formation. Apart from the above-mentioned mineral, pyrite, arsenopyrite, chalcopyrite, pyrrhotite, sphalerite and galena are also present, they contain numerous compounds of toxic heavy metals and arsenic. They include: Pb, Cu, Ni, Mn, Zn, Co, Cd, which migrate by the chain: waste → snow cover → soil → surface water → sediments → vegetation → human, in large quantities accumulated in environmental objects. They have been found to exceed regional background levels by a factor of 1.5–30 and more.

An analysis of the scale of the hazardous impact of mineral processing waste in the Primorsky Krai, especially on flora and fauna, shows that this impact takes different forms. Not only destruction of the small biological cycle, but also chemical pollution of all environmental objects, including biota, takes place due to arising secondary (technogenic) geochemical anomalies and dispersion flows of pollutants [1, 2, 5, 6, 7, 9, 10]. The results of space imagery analysis show that during 30 years of existence of the natural-mining-industrial technogenic system formed in the Kavalerovsky tin ore district there is a significant landscape degradation. Its area is more than 650 km². It has been revealed that technogenic contaminated areas of damaged (degraded) forest near Vysokoorsky tailing dump have increased from 5 to 9 times. The total area of intensive technogenic pollution of the forest area in the study region amounted to more than 300 km². Due to a high level of technogenic pollution of environmental objects there is a need to ensure their ecological safety. Forest ecosystems deserve special attention. Therefore, the sites were laid in the area under research to study phytomass growth using the Vega-Science tool of scientific analysis of satellite observation data developed at the Institute of Space Research of RAS [25]. The calculation of NDVI vegetation index value was performed, its value is determined by the leaf surface reflectivity of plants [26]. Using methods of automatic ERS data processing (calculation of NDVI vegetation index in QGIS geoinformation system) based on brightness analysis, multi-temporal NDVI "index" images were constructed, the state of landscapes was analyzed based on them. NDVI (Normalized Difference Vegetation Index) is a simple quantitative measure of the amount of photosynthetically active biomass (commonly referred to as the vegetation index). It is calculated using the following formula. According to this formula (1), the vegetation density (NDVI) at a given image point is equal to the difference between the intensities of reflected light in red and infrared band divided by their intensities sum. NDVI indices were determined at geo-referenced points with certain level of pollution. From literature sources it is known that dense vegetation corresponds to NDVI index value of 0.7, and sparse vegetation – 0.5 and lower. The results of our studies have shown that on the surface of Vysokoogorsky tailing dump containing toxic waste NDVI value was 0.066–0.13 (very sparse vegetation). The materials obtained allowed us to make a preliminary conclusion that the restoration of forest vegetation within the boundaries of the impact of the Vysokoogorsky toxic tailing dump does not take place in full scale. Further studies, including expeditionary geobotanical ones, are envisaged here to refine the results. The principles of ecological safety of biota and forest ecosystems, in particular, have been developed on the basis of theoretical and experimental research. In our opinion, to increase the ecological preservation of biota, forest ecosystems in the course of mineral development under the conditions of sustainable development of mining areas in the Far Eastern Federal District, a new environmentally safe technology based on the following principles is required: 1. Priority of ecological requirements consisting in carrying out a set of information, technological, biological, legislative and moral decisions in the process of Earth resources exploration and development; 2. Biodiversity preservation and restoration in the process of solid minerals development; 3. Protecting the gene pool, including biota and the human population; 4. Mining production development in accordance with the ecological capacity and self-restoration of natural ecosystems; 5. Overcoming ecological illiteracy and a consumer attitude towards natural, including mineral, resources; 6. Use of economic incentives for implementing environment friendly technologies and equipment; 7. Mining and environmental monitoring of ecosystems changes in the course of mining operations.

The researches made allowed to propose nature protection measures aimed at creation of new methods of forest reclamation for Vysokoogorsky tailings dump surface using bioremediation, novelty
of which is confirmed by the Patents of the Russian Federation [28-29]. The experimental studies show that reduction of the negative impact of toxic mineral processing wastes on the ecosphere objects from technogenic pollution caused by toxic wastes stored in the tailings dump and improvement of its surface reclamation efficiency is achieved, for example, by bioactivator applying [28]. This task included treatment of the tailings dump reclaimed surface with bioactivator (biological agent), sowing of legume-grass mixture, larch and buckthorn (Hippohae) seedlings planting, contouring of the tailings dump perimeter with water permeable borders and drainage ditches, creation of a forest protection belt around the technogenic object, and using phototrophic bacteria as a bioactivator (biological agent). The experiment was conducted under greenhouse and production conditions (on the tailings pond) in eleven replications: with application of phototrophic bacteria (PTB) on the toxic waste surface. The best results (in terms of biomass) were obtained in the variant with the PTB application (yield was 234 centners/ha). The experimental data show that the variant with the introduction of PTB contains a sufficient amount of energy in the form of organic matter and nutrients due to the activity of phototrophic bacteria, which contributed to the successful biological processing of the studied substrate. In addition, there was a binding of heavy metal compounds by organic matter carbon and immobilization of the main amount of heavy metal compounds to non-hazardous limits. In the variants without PTB application (control, toxic waste) no sprouts appeared. The solution of this problem was caused by a new technical result, consisting in highly effective activity of bioactivator (PTB) and is realized by interaction of PTB with substrate (toxic waste). Phototrophic bacteria help to improve water-physical properties of the substrate and, having no ability to organotrophic nutrition, extracellularly release various vitamins, nucleotides, amino acids and ATP, thus attracting other microorganisms, which help them to obtain low-molecular organic compounds necessary for their nutrition. This is one of the features and usefulness of PTB in eliminating toxic and harmful compounds for organisms. Beneficial PTB effect on soil structure formation as well as growth and development of plants (legume-grass mixture and larch) was revealed.

Successful results were obtained also using biochar and zeolites and biochar, zeolites and biohumus obtained from spent blocks of common oyster mushroom [29].

4. Conclusion

A general strategy to improve the ecological safety of biota, including forest ecosystems, must necessary be based on the principle of the need to forecast probabilistic forms of changes in all components of the biosphere caused by the impact of toxic tailing dumps on them. Computer modeling using GIS-technologies, as well as remote sensing of the Earth is the best tool for calculating such forecasting options with a comprehensive assessment of positive and negative factors acting on biota. These methods make it possible not only to implement traditional models of technogenic pollution transfer in space and time, but also to see forecast changes in the natural ecosystems state over long (several decades) periods of possible development under those or other strategies of technogenic impact and develop environmental protection measures. On the basis of the conducted research, the principles of biota ecological safety, including forest ecosystems, were proposed and we have developed the methods of forest reclamation of the tailings dump surface using the potential of biological systems, which novelty is confirmed by the Patents of the Russian Federation.

Acknowledgements

The study was performed by a grant from the Russian Science Foundation (Project No 15-17-10016), and with financial support from RFBR as a part of the Project No 18-35-00260

Reference

[1] Trubetskoi K N and Galchenko Yu P 2015 Geocology of subsurface development and ecotechnology of field development. (Moscow:Nauchtkhlitizdat), p 360
[2] Trubetskoi K N and Galchenko Yu P 1998 Sustainability of biological communities and
environmental safety of technologies for the development of the Earth's interior [Ustoichivost' biologicheskikh soobshchestev i ekologicheskaya bezopasnost' tekhnomii osvoiniya zemnykh nedr – in Russian] Gorny vestnik 5 pp 3–9

[3] Protasov V F and Vorob'ev A G 2006 Ecological problems in the strategy of sustainable development of the mineral resource complex of Russia [Ekologicheskie problemy v strategii ustoichivogo razvitiya mineral'nogo-syr'evogo kompleksa Rossii – in Russian] Gorny zhurnal 9 pp 73–76

[4] Mamaev Yu A, Kruskaya L T and Saksin B G 2005 Regulatory impact of biota on the natural environment and the problem of organizing biological research within natural mining systems [Reguliruyushchee vozdeistvie bioty na okruzhayushchuyu prirodnuyu sredu i problema organizatsii biologicheskikh issledovanii v predelakh prirodno-gornotekhnicheskikh sistem – in Russian] Mining information-analytical Bulletin, 3 pp 137–141

[5] Kruskaya L T, Grekhnev N I, Novorotskaya A G and Krupskii A V 2010 Features of migration of toxic chemical elements in the components of the natural environment in the zone of influence of the tailings plant JSC "solar GOK" [Osobennosti migratsii toksichnykh khimicheskikh elementov v komponentakh prirodnoi sredy v zone vliyaniya khvostokhranilishchha TsOF OAO «Solnechnyi GOK» – in Russian] Mining information-analytical Bulletin, 4 pp 349–361

[6] Shek V M 2000 Object-oriented modeling of mining systems. (Moscow: Moscow state mining University), p 304

[7] Kulikova E Yu and Sergeeva Yu A 2020 Conceptual model for minimizing the risk of water pollution in the Kemerovo region [Konseptual'naya model' minimizatsii riska zagryazneniya vodnykh resursov Kemerovskoi oblasti – in Russian] Mining information-analytical Bulletin, 6(1) pp 107–118

[8] Zhang B et al 2012 Application of hyperspectral remote sensing for environment monitoring in mining areas Environmental Earth Sciences, 65 pp 649–658

[9] García Millán V E, et al 2018 Monitoring Flooding Damages in Vegetation Caused by Mining Activities Using Optical Remote Sensing Journal of Photogrammetry, Remote Sensing and Geoinformation Science, 86 pp 1–13

[10] Zhu D et al 2020 Monitoring the effects of open-pit mining on the eco-environment using a moving window-based remote sensing ecological index. Environmental Science and Pollution Research, 27 pp 15716–28

[11] Xu J et al 2018 Remote sensing classification method of vegetation dynamics based on time series Landsat image: a case of opencast mining area in China. EURASIP Journal on Image and Video Processing, p 113

[12] Reddy G P O, Kumar N and Singh S K 2018 Remote Sensing and GIS in Mapping and Monitoring of Land Degradation. ed G Reddy and S Singh. Geospatial Technologies in Land Resources Mapping, Monitoring and Management. Geotechnologies and the Environment, 21 pp 401–424

[13] Goswami T and Sarma H 2020 Intelligent Computing for Air Pollution Monitoring Using GIS, Remote Sensing and Machine Learning. ed Hitendra Sarma Emerging et al Trends in Electrical, Communications, and Information Technologies. Lecture Notes in Electrical Engineering, 569 pp 125–133

[14] Gül M, Zorlu K and Gül M 2019 Assessment of mining impacts on environment in Muğla-Aydın (SW Turkey) using Landsat and Google Earth imagery. Environmental Monitoring and Assessment, 191(11) p 655

[15] Potapov V P, Giniyatullina O L and Schastlivtsev E L 2013 Modern approach to environmental monitoring of mining regions using methods of remote sensing of the Earth and cloud technologies [Sovremennyi podkhod k ekologicheskomu monitoringu gornodobyvayushchikh regionov s ispol'zovaniem metodov distantsionnogo zondirovaniya Zemli i oblacnychh technologii – in Russian] Mining information-analytical Bulletin, 6 pp 459–464
[16] Giniyatullina O L and Potapov V P 2014 Remote monitoring of environmental pollution [Distantionnyi monitoring zagryaznenii okruzhayushchei sredy – in Russian] Bulletin of the Scientific Center, 1 pp 142-148

[17] Potapov V P, Schastlivtsev E L, Giniyatullina O L, Kharlampenkov I E, Baskakov V P, Reutov I A, Popova M A and Shitushkina N V 2014 The creation of information-computational system for dynamic monitoring and evaluation of the environment [Sozdanie informatsionno-vychislitel'noi sistemy dinamicheskogo monitoringa i otsenki sostoyaniya prirodnoi sredy – in Russian] Bulletin of the Scientific Center, 1 pp 162-169

[18] Asmaryan Sh G, Muradyan V S, Tepanosyan G O, Ovsepyan A, Minasyan L and Sagatelyan A K 2015 The Practice of application of distance learning technologies in geo-ecological studies [Praktika primeneniya distantsionnykh tekhnologii v geologicheskikh issledovaniyakh – in Russian] Bulletin of the Scientific Center, 1 pp 142-148

[19] Shibalova G V 2010 The possibilities of using remote sensing to collect information about disturbed lands [Vozmozhnosti primeneniya distantionnogo zondirovaniya dlya sbora informatissii o narushennykh zemlyakh – in Russian] Environmental management, 4 pp 14-18

[20] Usikov V I and Ozaryan Yu A 2016 The use of remote sensing of the Earth in solving problems of geocology on the territory of the EAO [Ispol'zovanie distantionnogo zondirovaniya zemli v reshenii zadach geologii na territorii EAO – in Russian] In the book: Modern problems of regional development. Abstracts of the VI International Scientific Conference, pp 55-58

[21] Asmaryan Sh G, Muradyan V S, Tepanosyan G O, Ovsepyan A, Minasyan L and Sagatelyan A K 2015 The Practice of application of distance learning technologies in geo-ecological studies [Praktika primeneniya distantsionnykh tekhnologii v geologicheskikh issledovaniyakh – in Russian] Bulletin of the Scientific Center, 1 pp 162-169

[22] Zen'kov I V, Morin A S, Kiryushina E V, Vokin V N and Veretenova T A 2019 Restoration of the ecology of disturbed lands during the development of the Volchansk coal field based on the results of remote sensing [Vosstanovlenie ekologii narushennykh zemel' pri razrabotke Volchanskogo ugleob'yevozhdeniya po rezul'tatam distantionnogo zondirovaniya – in Russian] Coal, 10 pp 105-107

[23] Vernadskii V I 2012 Biosphere and noosphere. (Moscow: Airis-press), p 576

[24] Kolesnikov B P and Motorina L V 1978 Methods for the study of biogeocenoses in a technogenic landscape Program and methodology for the study of technogenic biogeocenoses [Programma i metodika izucheniya tekhnogennykh biogeotsenozov – in Russian] (Moscow: Nauka) pp 5-16

[25] Lupyan E A, Savin I Yu, Bartalev S A, Tolpin V A, Balashov I V and Plotnikov D E 2011 Satellite service for monitoring the state of vegetation ("VEGA") [Sputnikovyi servis monitoringa sostoyaniya rastitel'nosti («VEGA») – in Russian] Modern problems of remote sensing of the Earth from space, 8(1) pp 190–198

[26] Rouse J W, Haas R H, Schell J A, Deering D W, Harlan J C 1974 Monitoring the vernal advancement and retrogradation (greenwave effect) of natural vegetation NASA/GSFC Type III Final Report, Greenbelt, Md, p 371

[27] Zvyagintsev D G 1991 Methods of soil microbiology and biochemistry [Metody pochvennoi mikrobiologii i biokhimii – in Russian] (Moscow: State University Publishing House), p 304

[28] The patent No RU 2569582 C1 2015 Krupskaya L T, Kirienko O A, Maiorova L P, Golubev D A, Onishchenko M S A method for recultivating the surface of a tailing dump containing toxic waste using phototrophic bacteria [Sposob rekultivatsii poverkhnosti khvostokhranilishcha, soderzhashchego toksichnye otkhody, s ispol'zovaniem fototrofnykh bakterii – in Russian]

[29] The patent No RU 2707030 C1 2019 Krupskaya L T, Ichshchenko E A, Golubev D A, Kolobanov K F, Rastanina N K Composition for reducing the dust load on the ecosphere and recultivating the surface of the tailings storage facility [Sostav dlya snizheniya pylevoi nagruzki na ekosferu i rekultivatsii poverkhnosti khvostokhranilishcha – in Russian]