Improving the Efficiency of Forestry Measures for Carbon Storage by Reclamation and Phytomelioration of Lands Technogenically Contaminated with Toxic Tailing Wastes

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Abstract. The article presents the results of multi-year research on technogenic pollution of biosphere components with wastes of cassiterite-sulfide formation processing. The areas of mainly Far Eastern taiga and Priamurye-Primorye coniferous-broad-leaved forest in the Far Eastern Federal District (FEFD) of Russia have been withdrawn from the forest land fund for their development. As a result, large amounts of mining waste have been accumulated, with negative impact on forest ecosystems. In this regard, the aim of the study was to substantiate forestry measures for improving their efficiency by reclamation and phytomelioration of technogenically contaminated lands with toxic mineral processing waste to accumulate carbon stock. The analysis and systematization of the literature and patent search materials testify that the article is devoted to the actual problem of carbon stock accumulation within the impact boundaries of the technogenic system by reclamation and phytomelioration. These problems in the conditions of mining enterprises of the Far Eastern Federal District of Russia are poorly studied. It is shown that the mineral development by the mining enterprises closed in the last century led to the large-scale destruction of forest communities. Methods of reproduction of productivity of technogenic polluted lands using bioremediation which novelty was confirmed by Patents of the Russian Federation are developed. By means of their reclamation and phytomelioration an increase in forestry measures and accumulation of carbon stocks in the reclaimed lands was achieved by more than 2.5 times in comparison with the nonreclaimed lands.

1. Introduction
In the last century in Russia and the Far Eastern Federal District in particular, intensive mineral development by mining enterprises of the lands from the forest land fund being withdrawn for it, has contributed to natural-mining technogenic system formation. It contains large volumes of toxic, highly sulfidized wastes and environmental facilities. Stored in tailing dumps near settlements, they caused large-scale technogenic pollution of ecosphere and appearance of environmental-related diseases of population. The processes of soil and vegetation cover degradation and destruction, as well as deforestation of vast areas and loss of carbon stocks occurred [1] (Zamolodchikov and et al., 2019). In this regard, the need to restore the productivity of lands disturbed by solid minerals development by
reclamation and phytomelioration has appeared. Russian and foreign researchers have proposed different methods. Thus, Y. I. Gorbunova [2] (2008) has shown that pine-tree plantations, created on overburden rock dumps, have high capacity of biological cycle intensity and are the atmospheric C-CO₂ sink. By the age of 20 years, they accumulate significant amount of carbon in the main ecosystem blocks and are able to perform biospheric and environment-forming functions.

V.I. Ufimtsev [3] (2013) in his article presents the results of the study of the above-ground phytomass of Scots pine plantations growing at the reclamation sites of coal deposits in Kuzbass. The parameters of stand density for successful atmospheric carbon deposition were determined. It was found that the density of Scots pine stands of the II age class on reclamation land from the position of carbon deposition is the most optimal density in the range of 1 thousand trees per hectare.

Studies by D.N. Klevtsov and O.N. Tyukavina [4] (2018) in the Vologda region indicate that the assessment of the carbon-depositing capacity of fractions of pine plantations phytomass of artificial origin varies by forest types. The carbon-depositing ability of above-ground phytomass fractions of the Scots pine crops tree layer increases with the improvement of forest site conditions. Thus, in the bilberry pine forest, the combined carbon is 1.77 t/ha, and in the lichen pine forest is 0.42 t/ha/year. The largest proportion of carbon deposited by fractions of above-ground phytomass falls on the trunk wood (60-76%). The next largest carbon-depositing phytomass fraction is woody green (7-14%). Bark and branches deposit carbon in roughly equal proportions. The smallest proportion is in the dry branches fraction (2-7%).

In 2016-2017 S.B. Vasiliev et al. [5] (2018) determining the carbon-depositing capacity of forest crops, laid the sample plots for experimental forest crops of Voskresenskiy forestry enterprise, Moscow region, on reclaimed lands. It was revealed that in the process of forest land reclamation the economic value of lands disturbed in the course of industrial production was restored. The forest plantations of various types and purpose are planted on such lands, and the forest fund increases. The authors concluded that the data obtained can be used to form a data bank on carbon stock in woody plants phytomass during forest reclamation of disturbed land. Using information on the plantations age structure, the productivity and growth of woody plants, it is possible to estimate the carbon dioxide storage and deposition capacity of a particular species in the region in question.

The results of studies carried out on reclaimed plots in the Far Eastern Federal District are of scientific interest [6].

J. Ahirwal et al [7] (2018a) conducted a field study to assess the impact of vegetation cover on Technosol quality at post-mining sites (Central Coalfield Limited, India). The study assessed the community structure, biodiversity, technosol quality and carbon (C) dynamics in the ecosystem. The results of the study indicated that restoration of secondary forest by planting fast-growing tree species showed a significant improvement in technosol quality along with plant biodiversity, which contributes to restoration of soil functions. The study allowed the authors to claim that re-vegetation of land after mining is particularly promising for increasing carbon sequestration and compensation of the global warming negative impact.

A field study by J. Ahirwal et al. [8] (2018 b) evaluated the in CO₂ flux in soil changing in winter season also, although a long-term study of CO₂ flux in soil in post-mining area is recommended to understand the CO₂ flux changing. A study of the problem was conducted on unmined and reclaimed coal mine land to assess changes in the CO₂ flux in the soil and compare it with a reference forest site. It was found that the higher CO₂ flux in the reclaimed soil (RMS) is associated with a large root biomass. The authors believe that the findings can be useful for understanding the ecosystem carbon dynamics after mining and the role of afforestation in carbon sequestration.

R. Das et al. [9] (2016) consider that reclaimed land (Jharia Coalfields, India) provides an excellent opportunity to sequester carbon and combat global warming. Carbon sequestration in reclamation sites depends on rock composition, geodetic conditions, soil characteristics and the prevailing climate. The reclamation process is an integral part of mining operations aimed at stabilizing degraded mine sites, resulting in carbon sequestration. The carbon stock in the reclaimed soil depends on the nature and type of soil, vegetation and geoclimatic conditions. Based on their research, the authors made the following
prediction: the carbon stock in the forest crops grown on the reclaimed areas will tentatively reach the level of the reference forest plot in 17 years.

Results of the reclamation problem study by C. Hou et al. [10] (2021) suggest an important role for carbon storage by vegetation, and emphasize the importance of soil inorganic carbon in the carbon balance and the crucial importance of the arable layer in carbon accumulation. Moreover, the authors believe that soil carbon accumulation is closely related to its size texture, which varies continuously and is often determined by the spatial heterogeneity of coastal floodplains.

On the basis of the analysis, generalization and systematization of literary sources and patent search materials we have revealed that in Russia and abroad the solution of the problem of increasing the forestry measures efficiency for carbon stock accumulation by reclamation and phytomelioration of technogenically polluted lands with toxic tailing wastes is practically at the initial stage. In this regard, the aim of the study was to substantiate forestry measures aimed at improving their effectiveness by reclamation and phytomelioration of technogenically contaminated lands with toxic mineral processing waste, for the carbon stock accumulation. The following tasks are defined: 1. To analyze and generalize the existing experience in solving the above mentioned problem; 2. To assess the danger of tailing dumps as sources of ecosphere technogenic pollution; 3. To calculate the carbon balance on the reclaimed and non-reclaimed sites and to develop proposals for reducing technogenic pollution of the ecosphere and increasing the carbon balance.

2. Object and methods of research

Natural-mining systems, formed in the last century by economic activity of the mining enterprise are the object of research.

In the course of the research standard methodological approaches were used: forestry, forestry-taxation, geo-ecological, statistical ones.

The following methods for the Programme implementation were used: theoretical analysis of domestic and foreign literature and scientific forecasting, as well as empirical, structural, functional and system analysis.

The work used informational legal and literary sources, including the Fundamentals of National Policy for Use, Conservation, Protection and Reproduction of Forests in the Russian Federation until 2030. [11], Forecast of Development of the Forest Sector of the Russian Federation up to 2030. [12], Strategy of Scientific and Technological Development of the Russian Federation, approved by the Presidential Decree No. 642 of 01.12.2016. [13], etc.

Scientific, statistical, report data and other branch materials containing relevant information on the characteristics, condition and dynamics of forest land in the studied forest areas, forest use and processing, data on forest conservation, protection, and reproduction were used to carry out this work. Calculation of carbon stocks was carried out by the RECBF (Regional Evaluation of Carbon Budget of Forests) system [1]. The materials of the State Forest Inventory (SFI): Characteristics of Forests by Purpose: About Protective Forests, their Categories, Commercial Forests and Reserve Forests and Distribution of Forest Area and Timber Reserves by Dominant Species and Age Groups. Using the SFI, the information on areas and stock of plantations for forest-covered lands was obtained, as well as information on areas of different categories, unforested and non-forested lands of the Forest Fund (burnt areas, meadows, cuttings, etc.). The calculation was carried out for the pools of growing stock phytomass, dead wood (debris), litter and soil organic matter.

The content of the materials complies with the requirements of the international agreements signed by the Russian Federation.

3. Results and discussion

According to the RF Government Decree No. 800 of July 10, 2018, On Land Reclamation and Conservation, reclamation of land disturbed by legal entities, individual entrepreneurs and individuals is carried out at the expense of legal entities, individual entrepreneurs and individuals in accordance with approved land reclamation projects.
As a result of mineral development in the south of the Far Eastern Federal District (Amur Region, Khabarovsky and Primorsky Krais (Territories), more than 800,000 hectares of land have been disturbed, most of it was taken from the forest lands of the Far Eastern taiga and Primorye-Primorye coniferous-broadleaf forest areas of the Far Eastern Federal District (FEFD) of Russia. Large areas of valley forest have been destroyed. Reclamation of disturbed lands is practically nonexistent. At the best, industrial rubbish is partially removed, and the area disturbed by mining is planned, which does not meet environmental requirements.

A great danger for the environment is posed by the toxic highly sulfidized mineral processing wastes, stockpiled in tailings on productive areas, their mineral composition is due to the ore mineral composition. They contain pyrrhotite, pyrite, chalcopyrite, galena, sphalerite, etc. The chemical composition of waste is characterized by high content of zinc, lead, copper, etc. Waste hazard class is 2 (highly hazardous). They are technogenically generated, formed from substances that do not occur in the earth's crust or with an admixture of such. The waste is dry and easily moved by the wind. The granulometric composition of the deposits is very heterogeneous. It is an alternation of silty, pelitic and sandy fraction layers. It is here that increased accumulations of sulfide and other ore minerals should be expected. Good aeration and water permeability of tailing wastes and relatively short periods of their storage provide loose accumulation, which contributes to intensification of sulfide minerals oxidation and leads to large-scale technogenic pollution of the ecosphere. Exceedance of background indicators and MPC of soils, vegetation, water bodies from 1.5 to 40 and more was found. As our studies have shown, it is no coincidence that, the studied toxic substratum, tailings, surface have not practically being overgrown naturally for 30 years. This involves negative consequences, including intensive technogenic pollution and the carbon balance violation.

At present, there is a need to develop the technology for reclamation of disturbed toxic mineral processing wastes stockpiled in the tailings of previously closed mining enterprises, to return the withdrawn areas to the forest fund lands. Their self-overgrowing is practically impossible due to unfavorable agrophysical and chemical properties of the material of this technogenic facility, toxicity of surface layers for plants, absence of organic matter. The possibilities of accelerated creation of effectively functioning soil-ground horizons, as the most important structural unit, of restored biogeocenoses on the worked-out areas have not been studied. The existing experience of researching the reclamation problem in the country and in our region shows that there are practically no research papers of constructive critical reclamation estimation and practical application of alternative methods and technologies of reclamation at the territory of the region under consideration. The main task of forest reclamation in the FEFD is to bring the situation as close to the original state as possible. Of course, it is impossible to return the original substance, but to close aquifers exposed by residual quarry excavations, in which lakes are formed due to discharge of subsurface water, is extremely necessary above all. Otherwise, the annual losses of both surface water and groundwater will be ensured. In this regard, the most important task is the creation of conditions for accumulation of carbon and organic matter, formation of a humus layer and normal development of plants on the reclaimed surface.

In addition, in most cases, the reclamation rate at mining enterprises in the Far Eastern Federal District is extremely low and significantly lags behind the volume of land disturbance. However, the applied reclamation technologies have a low level of knowledge-intensiveness and ecological efficiency, which do not allow to reduce significantly the negative impact of disturbed lands on the adjacent forest areas. It is obvious that a new approach is also required in the organization of reclamation operations for creating forest ecosystems on the surface of the tailing dump, for which the lands of the forest fund were withdrawn. Our surveys of disturbed lands allow us to conclude that land reclamation in the FEFD are carried out in insufficient volumes and with low efficiency, without a preliminary assessment of forest regeneration processes and the technogenic pollution impact on forest complexes of adjacent territories.

In order to reduce the negative impact of tailing dumps containing toxic waste and to increase carbon accumulation, it is necessary to carry out timely the technical and biological stage of reclamation on lands after mining.
Taking into account modern scientific developments of reclamation technology, technological schemes and mechanical equipment of the technical stage of reclamation must meet the following basic requirements: 1. Creation of the optimal relief for the designed direction of the reclaimed land use; 2. Formation of the root-inhabited reclamation layer of rocks with properties favorable for growth and development of plants on the beach area; 3. Creation of the favorable hydrogeological regime; 4. Erosion protection of the reclaimed territory.

Thus, the technical stage of land reclamation provides the conditions for carrying out the following stage of biological reclamation in the direction set up by the project.

The technical stage of reclamation includes the following types of operations: 1. Coarse and fine leveling of the surface, its repair; 2. Counter-erosion organization of the territory, including slopes; 3. Toxic rocks amelioration; 4. Application of potentially fertile rocks (if necessary).

To prevent over-compaction of the reclaimed area surface, mining and land-leveling works are carried out by machines with low specific pressure on the ground. Repair of reclaimed sites is provided in case of relief unevenness as a result of rock contraction or erosion processes. These works are performed both prior to application of a potentially fertile layer on the surface and in the process of biological reclamation.

At the biological stage, the measures are taken to reproduce the productivity of disturbed lands and increase carbon accumulation in the managed forests of the Far Eastern taiga and Primorye-Primorye coniferous-broad-leaved forest areas. They are a set of agro-technical and phytomeliorative measures aimed at renewal of flora and fauna and creation of sustainably functioning bioceneses.

An innovative approach was used for the biological stage of the reclaimed area created on the surface of toxic waste tailings. It was found that in the complex of biological reclamation methods it is necessary to pay special attention to the enrichment of substrate with organic matter. In this regard, the researchers of FEFRI (Far East Scientific Research Institute of Forestry) recommended using the biological system potential (bioremediation), namely: phototrophic bacteria, humic compounds, compost with a cultivated strain of basidium fungi [14-16], etc.

The correct selection of shrub and tree species, as well as species of perennial herbaceous plants is important. The most promising, experimentally tested, and recommended for the conditions of the southern part of the Far Eastern Federal District (FEFD) among the significant number of species is native woody and shrub vegetation. Herbaceous plants include creeping couch grass, timothy grass, wormwood, awnless brome, yellow sweet clover, Dutch clover and meadow fescue.

Some experience has been accumulated in the forest areas under study in recreating the productivity of natural ecological systems disturbed by mineral development [76, 134-136, etc.]. Experimental studies on the reclamation of disturbed areas were carried out in typical conditions for the forest areas under consideration. This is the Kerbinsky gravel mine, for the development of its gold deposits the lands of the forest fund of the Far Eastern taiga forest area were withdrawn. This mining enterprise reclaimed disturbed lands in 1988 after mining operations were completed using soil microorganisms and humic preparations and mixtures (Fig. 1a).

The lands of the Primorye-Primorye coniferous-broad-leaved forest district were withdrawn for the Korfovsky stone quarry developing the granodiorite deposit. Forest reclamation using soil microorganisms and humic acids was carried out on its waste dumps in 1988 (Fig. 1b).

On the areas reclaimed in 1988 and the lands left under natural self-overgrowing, the carbon stock in the newly formed plantations was calculated according to the RECBL system method [1]. The results are presented in tables 1 and 2. The calculations show a significant accumulation of carbon stock in phytocenoses formed on the reclaimed lands (Tables 1 and 2) compared to the uncultivated ones.
Figure 1. State of tree and shrubbery vegetation on the areas reclaimed in 1988: a) Kerbinsky gravel mine; Korfovsky stone quarry.

Table 1. Carbon stock in plant communities formed on reclaimed in 1988 areas disturbed by alluvial and granodiorite mining in Khabarovsky Krai (Kerbinsky gravel mine), t C.

| Carbon pool | Non-reclaimed area | Aspen (Khelok river outlet in Kerby river) | Birch forest with aspen, alder and willow (Kerby river) |
|-------------|-------------------|------------------------------------------|-----------------------------------------------------|
| Stand biomass | 2                 | 22                                       | 64                                                  |
| Dead wood    | 0                 | 1                                        | 3                                                   |
| Litter       | 2                 | 3                                        | 7                                                   |
| Soil (0-30 cm) | 30              | 80                                       | 116                                                  |
| Total        | 34                | 106                                      | 190                                                  |

Our research suggests that the main task for increasing the amount of CO₂ deposited in the forest is to help increase the primary productivity of forest ecosystems. For this purpose, various methods are used, including phytomelioration in treeless, potentially forested, and low-productive areas of forest land by creating forest strips from the most fire-resistant plantations (poplar and larch).

Table 2. Carbon stock in pilot forest of Khekhtsir experimental forestry enterprise of the Far East Scientific Research Institute of Forestry after phytomelioration, t C /1 ha.

| Carbon pool   | Carbon stock before draining | Carbon stock after draining |
|---------------|------------------------------|----------------------------|
| Stand biomass | 8                            | 41                         |
| Dead wood     | 0                            | 2                          |
| Litter        | 4                            | 6                          |
| Soil (0-30 cm)| 55                           | 71                         |
| Total         | 67                           | 120                        |

Note: Table 2 is compiled taking into account the carbon stock per 1 hectare area, by RECBF system method using the indicators (area, stock and composition of the stand) within the boundaries of the study area.
Considering the extreme fire danger and combustibility of forest plantations in the Far Eastern Federal District, it is necessary to introduce measures to create fire-resistant protective strips of poplar or larch [17] as the main direction of phytomelioration and fire protection in the region. Fire protection strips begin to perform firefighting functions immediately after the trees closure in the rows. Larch strips in the zone of coniferous-broadleaved forests acquire fire protection properties in the 4th-5th year, in the taiga zone in 5th-7th year. Poplar strips act one year earlier. In general, protective firebreaks should perform their firefighting functions for 40 years without significant forestry measures. Positive economic effect of protective firebreaks (PFB) without taking into account the prevented damage from forest fires appears after 15 years in comparison with mineralized firebreaks. It was found that after 30 years, the effect of them fully covers their creation costs. PFBs perform a complex of protective and ecological functions, including the accumulation of significant stocks of wood, including carbon.

4. Conclusion
To reduce the negative impact of deforested areas resulting from mineral development and to increase carbon stock accumulation, reclamation (technical and biological stages) was carried out using the biological systems potential (bioremediation), the novelty of which has been confirmed by the patents of the Russian Federation [148, 149]. Considering the extreme fire danger and the flammability of forest plantations in the Far Eastern Federal District, it is recommended to implement measures for creation of poplar or larch fire-resistant protective strips by phytomelioration.

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