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The Impact of Soil Improvers on the Biological Remediation of Disturbed Landscapes in the Context of Pronounced Erosion Processes

E.A. Dyukova[1], M.A. Osintseva[2*]

[1]Kemerovo State University, 6 Krasnaya Street, Kemerovo, 650000, Russia;
+7-384-2-386932;
Email: jeniadulova@mail.ru, *pavvm2000@mail.ru,
Corresponding Email: pavvm2000@mail.ru

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ABSTRACT:

Abstract. The land of coal companies becomes unsuitable for further agricultural activities. Biological remediation is used to restore them. This study aimed to investigate the effect of soil improvers on plant establishment during biological remediation of disturbed landscapes in conditions of pronounced erosion processes. The present study analyzes the maturation processes of cultures in dynamics based on geospatial materials and maps of normalized relative vegetative index in biological remediation of the site of cultivated plant species and their positive response to the use of pre-sowing seed treatment with biological soil improvers and growth regulators. When the results of experiments on sites with varying degrees of preparation during the mining phase of remediation were compared, it was discovered that sites hydroseeded with a grass mixture had the highest efficiency in terms of survival rate and biomass growth. At the same time, the best result for hydroseeding was observed in plots with the application of a potentially fertile soil layer (loam). It was also found that the planting of trees and shrubs on the site with the application of loam and sector of technogenic eluvium slows down the initial vegetation process due to a longer period of plant adaptation, but does not have a great impact on the plant establishment. The data on biological remediation with soil improvers obtained from the experiment will be used for further analysis to determine the best phytoremediation technology for disturbed landscapes in conditions of severe erosion processes.

Keywords: Coal dumps, Phytoremediation, Biopreparation, Sapropel, Rhizobacteria, Orthophotoplan.

1. Introduction

Kemerovo Region is the leader of the Russian coal industry, accounting for half of Russia's coal production and 70% of coal exports. In 2022 alone, coal production amounted to 223.3 million tons, which is 50.8% of all coal produced in the country (Petrenko, 2023). The existing reserves of 54,649.9 million tons of coal will provide the companies with another 200 years of continuous coal mining, which will inevitably affect the reduction of natural landscapes in the area. The coal industry is one of the most ecologically complex sectors of the national economy, which has a negative impact on the entire ecosystem of the region. In this case, the anthropogenic impact on the environment results in pollution of the atmosphere, water, soil, and adjacent land. The wastelands become unsuitable for further agricultural activities, the fertile layer vanishes entirely, and flora and fauna are destroyed. This has a profoundly negative impact on the population's sanitary and hygienic living conditions. Pathologies associated with unfavorable ecology account for up to 20% of deaths (Petrenko, 2023).

The significance of maintaining the quality of the environment, including the remediation of disturbed lands and the restoration of their soil-ecological functions, is determined by the region's tense ecological situation (Nevskaya et al. 2019). According to the Rules of Land Reclamation and Conservation approved by the Government of the Russian Federation, reclamation should be considered as a measure to prevent land degradation and/or to restore its fertility by bringing the land into conformity with its intended purpose and permitted use, including by eliminating the consequences of soil contamination, restoring the fertile soil layer, and creating protective forest plantations (Yurchenko, 2020).

The first stage of remediation is technical, which entails the necessary landscape adjustment (development of the works project, formation of slopes, terraces, utilization of stone waste, ensuring soil stability (flattening), application of fertile soil layer, construction of reclamation and hydraulic engineering structures, roads, etc.) (Zenkov *et al.* 2020).

The next stage of remediation is biological. It includes a set of agrotechnical, phytomeliorative, and other measures that will restore the ecological functions of soils, biological productivity, and species diversity of ecosystems (Zenkov *et al.* 2020). Such activities include seeding lawns or other vegetation, applying organic fertilizers, and protecting soils from wind erosion.

Thus, remediation is a rather complex technical, costly, and time-consuming process that necessitates a comprehensive approach to analyzing multiple characteristics of the waste area in order to plan competently and achieve the effectiveness of remediation efforts (Andrade, 2022).

Given the complexity of the remediation process, it is advisable to consider various innovative technologies as a decision-making tool when planning and implementing activities (Mulyono *et al.* 2021).

Restoration of natural landscapes disturbed by coal mining is an indefinite process, so promising remediation technologies aim to achieve a certain level of similarity of technogenic ecosystems to natural ones. The decision regarding the direction of remediation and the optimal use of the waste dump territory should be made at the time of land allotment, based on comprehensive economic, environmental, biological, and technical feasibility. In the event that restoration of the original state of the territory is not possible, the necessary compensatory measures must be taken into account (Kopytov and Shaklein, 2018).

The plantations established on previously disturbed lands can be diverse in their purpose (Zenkov *et al.* 2020). In case of forest recultivation they can be forest husbandry, protection, water protection, recreational, sanitary-hygienic, or elements of other directions of agriculture, fishery, water management, construction, etc. (Kopytov and Shaklein, 2018). However, in all cases, they serve a conservation purpose by improving the ecological conditions of a previously disturbed site (Nevskaya *et al.* 2019).

One of the primary prerequisites for the successful restoration of former biodiversity is the restoration of the fundamental characteristic of natural landscapes, namely soil cover. Therefore, the purpose of biological remediation is to establish vegetation cover on reclaimed land, restore the fertility of reclaimed soils, create favorable environmental conditions, and return disturbed land to the land user. The green cover has protective and, in populated areas, decorative functions.

The effectiveness of industrial landscape remediation is determined by the appropriate crop selection and the addition of soil improvers (Nevskaya *et al.* 2019). The objective of environmental optimization requires the establishment of phytocenoses in industrially disturbed landscapes with high productivity and actively performing phytomeliorative role in the first years of development of disturbed lands (Sivkova and Kalinina, 2018). When selecting plant species and soil improvers for reclamation, it is essential to consider a range of factors, including bioecological features, ecological plasticity, growth and development rates, and the ability to reproduce and regenerate (Osipov, 2018).

The objective of this study was to assess the impact of soil improvers on the establishment of plants during the biological remediation of disturbed landscapes in the context of pronounced erosion processes.

2. Materials And Methods

Object of Research

The experimental test site was situated at the Kazachenkovsky dump of the Kazachenkovsky coal mine of the Talda coal mine (Tayezhnoe Pole) of JSC Kuzbassrazrezrezugol (Kemerovo region, Prokopyevsky district, Bolshaya Talda village). The study area was the area adjacent to the dump at the boundary with the haul road.

Remediation Design

The preliminary mining and technical stage of remediation was conducted on the territory of the test site by Kuzbassrazrezugol. In order to establish a scientific foundation for the experiment, the surface was cleaned and a layer of potentially fertile soil layers (PFSL) with a minimum thickness of 1 m and a layer of fertile soil (FSL) with a minimum thickness of 0.5 m was applied. Irrigation with sprinkler systems was used for agronomic management of the experimental plant material during the growing season.

In all plots, the treatment of seeds of perennial grasses and root systems of tree and shrub species with a complex of rhizosphere bacteria (b/p) developed in the Laboratory of Genomic Research and Biotechnology of Kemerovo State University (Russia) was introduced into the experimental design. In the second variant, a microbiologically active preparation based on animal waste TOR-organic (Russia) was employed as a plant growth and development regulator. Sapropel (Eco-Vector, Russia) was used as a soil improver.

Hydrogel granules of 1-4 mm fraction (Vud Master, Russia) were used to keep moisture and nutrients in the root space during the period of rooting of seedlings and saplings of tree and shrub species in industrially disturbed soils.

Geosynthetic grid (Geonor, Russia) and latex suspension (Ruskhimneft, Russia) were used for soil reinforcement at the experimental site.

The supplementation experiment was conducted in triplicate (Liu et al. 2022). The total experimental site area was 10500 m^2. The area of the experimental plot was 300 m^2. The design of the experiment on the application of soil improvers is presented in Table 1.

Table 1: Design of the soil improver application experiment

Component	**Application**
Sapropel	Continuous layer superficially, at the rate of 200 kg/ha
Latex	7% water emulsion of latex, in the amount of 1.5-3.0 L/m^2
Microorganisms	Water solution in the amount of 1.5-2.0 L/1000 L
Sapropel+microorganisms	Continuous layer superficially, at the rate of 200 kg/ha + water solution in the amount of 1.5-2.0 L/1000 L
Latex+microorganisms	7% aqueous emulsion of latex, in the amount of 1.5-3.0 L/m^2 + water solution in the amount of 1.5-2.0 L/1000 L
Control	-

The area was terraced and partial self-overgrowth of terrace sides was observed with grass cover of depleted species composition, which was previously removed by cutting off the topsoil.

Determination of Sowing Qualities of Seeds

Prior to commencing the experiment, a mixture of seeds was prepared and their viability was checked. To determine the germinating capacity, 100 pieces of seeds of each species were placed in pre-prepared Petri dishes. Seeds were placed on a layer of paper, 100 in each dish and covered with abundantly moistened filter paper. Seeds were watered every 48 hours. The process of swelling of seeds of herbaceous plants was observed after 34 hours, and that of seeds of trees and shrubs – after 54 hours. On the sixth day, the number of germinated seeds reached 56% of the total mass. Ten days after the experiment was established, the number of germinated seeds was counted (Ren *et al*. 2023).

Randomized Experiment

Experimental plots 1, 2, and 3 were established on 27.07.2023. The experimental plots were hydroseeded with a mixture of crops. The vegetation observation period for all plots was 72 days. The randomization design of the experiment is presented in Table 2.

Table 2: Randomized experiment design

1	**2**	**3**
no hydrogel; 25 kg of cellulose mulch; 4 kg of GrowMix mixture	1 kg of hydrogel; 30 kg of cellulose mulch; 4 kg of GrowMix mixture	2 kg of hydrogel; 40 kg of cellulose mulch; 4 kg of GrowMix mixture

Plots 1 (PFSL+FSL), 2 (PFSL), and 3 (industrial eluvium without application) were hydroseeded with perennial grasses at the rate of 225 kg/ha and planted with tree crops and shrubs (including fruit and berry crops). The species and quantity composition of planting material is presented in Table 3.

Table 3: Experiment establishment design

Planted cultivations	**Number / area (pcs/ha)**
Plot 1	
Hydroseeding of grass mixture: *Festuca rubra* 7%, *Bromopsis inermis* 7%, *Melilotus officinalis* 7%, *Elymus repens* 7%, *Festulolium* 7 %, *Phleum pratense* 10%, *Agropyron cristatum* 7 %, *Dactylis glomerata* 7 %,	0.1 ha

Trifolium repens 7 %, *Lupinus perennis* 13 %, *Onobrychis arenaria* 7 %, *Vicia sativa* 7 %, *Medicago sativa* 7 %	
Pínus sylvéstris	75
Pínus sylvéstris with biopreparation	75
Pópulus nígra	45
Pópulus nígra with biopreparation	45
Salix caprea	40
Salix caprea with biopreparation	40
Caragána arboréscens	30
Caragána arboréscens with biopreparation	30
Arónia melanocárpa	40
Arónia melanocárpa with biopreparation	40
Berberis thunbergii	60
Berberis thunbergia with biopreparation	60
Plot 2	
Caragána arboréscens	36
Caragána arboréscens with biopreparation	32
Ribes alpinum	26
Ribes alpinum with biopreparation	10
Pínus sylvéstris	73
Pínus sylvéstris with biopreparation	59
Pópulus nígra	24
Pópulus nígra with biopreparation	25
Arónia melanocárpa	19
Arónia melanocárpa with biopreparation	5
Berberis thunbergii	39
Berberis thunbergii with biopreparation	34
Physocarpus opulifolius	25
Physocarpus opulifolius with biopreparation	24
Hydroseeding of grass mixture: *Festuca rubra* 7%, *Bromopsis inermis* 7%, *Melilotus officinalis* 7%, *Elymus repens* 7%, *Festulolium* 7 %, *Phleum pratense* 10%, *Agropyron cristatum* 7 %, *Dactylis glomerata* 7 %, *Trifolium repens* 7 %, *Lupinus perennis* 13 %, *Onobrychis arenaria* 7 %, *Vicia sativa* 7 %, *Medicago sativa* 7 %	0.1 ha
Plot 3	
Hydroseeding of grass mixture: *Festuca rubra* 7%, *Bromopsis inermis* 7%, *Melilotus officinalis* 7%, *Elymus repens* 7%, *Festulolium* 7 %, *Phleum*	0.1 ha

pratense 10%, *Agropyron cristatum* 7 %, *Dactylis glomerata* 7 %, *Trifolium repens* 7 %, *Lupinus perennis* 13 %, *Onobrychis arenaria* 7 %, *Vicia sativa* 7 %, *Medicago sativa* 7 %	
Pínus sylvéstris	75
Pínus sylvéstris with biopreparation	50
Pópulus nígra	23
Pópulus nígra with biopreparation	22
Caragána arboréscens	32
Caragána arboréscens with biopreparation	32
Salix caprea	34
Salix caprea with biopreparation	34
Arónia melanocárpa	17
Arónia melanocárpa with biopreparation	17
Berberis thunbergii	37
Berberis thunbergii with biopreparation	37
Ribes alpinum	6
Ribes alpinum with biopreparation	5
Lonicera dioica	5
Lonicera dioica with biopreparation	5

Half of the planting material of each species and half of the hydroseeding area was treated with biopreparation. When planting saplings and seedlings, the biopreparation was applied as root irrigation. When treating hydroseeded sectors, biopreparation was applied in half the volume of substrate used.

Hydroseeding Experiment

Three variants of an experiment on hydroseeding were established, with each variant being replicated three times. The experimental plots, each measuring 100 m², were planted with seeds that had been treated with different active substances, which were expected to stimulate seed growth. A series of experimental trials were conducted utilising the hydroseeding unit Turbo Turf HS-1000 series. The hydroseeding mixture GrowMix80 (AFR-Group) and cellulose mulch for hydroseeding Re-Mat were employed as the substrate base for the hydroseeding. The technological process of hydroseeding was as follows. The tank was filled with water through a designated filling port. The accompanying hydroseeder engineer disconnected the plug from the water meter and attached the suction hose, the other end of the hose with the filter was lowered into the water. The filter was used to prevent the working nozzle from clogging when spraying the working mixture. After preparing the working mixture, the hydroseeder was brought to the area for material loading. After loading all materials, the hatch of the filler neck was closed, the working mixture was thoroughly mixed, the agitator was turned off and the work process was started.

Tree species were planted according to the pattern of 2 x 2 m, shrubs – according to the pattern of 1.5 x 1.5. After the seeding activities, field germination of the seeds was monitored every 10 days.

When planting saplings and seedlings, biopreparation was applied via root irrigation. In the treatment of hydroseeded sectors, biopreparation was applied in half the volume of substrate used. The vegetation of the planted material was observed using both a visual method and the normalized relative vegetation index (NDVI), with measurements taken at a frequency of once every two weeks.

Aerophotogrammetric Survey

Red, Green, Blue camera aerial photography (RGB camera) was performed using unmanned aerial vehicles (UAVs) Flight task design was performed in FLY Teofly software (software of Teokit modernization kit manufacturer). The flight was performed with terrain envelopment. The projected flight altitude relative to the terrain was determined to be 100 m. Photo overlap: 79% (longitudinal) x 60% (transverse). Projected spatial resolution of photographs: 2.6 cm/pixel. The designed flight task was imported into the Litchi flight execution software (Mironov & Tereshkin 2022).

Office study consisted of: processing of geodetic measurements made during the establishment of completion survey, calculation of coordinates and altitudes of the centers of projections of aerial photographs; photogrammetric processing of aerial survey materials, as well as the creation of maps of intra-field slopes on the basis of the resulting digital terrain (relief) model and calculation of the average slope of the sites.

Construction of Digital Orthophotos, Height Maps, Digital Terrain Models (Relief)

Digital orthophotomaps, height maps, digital terrain (relief) models in the form of dense point clouds were built on the basis of aerial images from RGB camera. NDVI maps were constructed on the basis of multispectral images. NDVI is a numerical measure of the actual quality and quantity of vegetation at a given site, which is determined by comparing the intensity of red light absorption and near-infrared light reflection by plants. Healthy plants tend to absorb red light and reflect near-infrared light (Sheremetova 2016).

Possible index values range from -1 to +1:
From -1 to 0 – are inanimate objects;
From 0 to 0.2 – are characteristic of open soil;
From 0,2 to 0.5 – scattered vegetation;
Over 0.5 – dense vegetation.

Development of Geospatial Materials

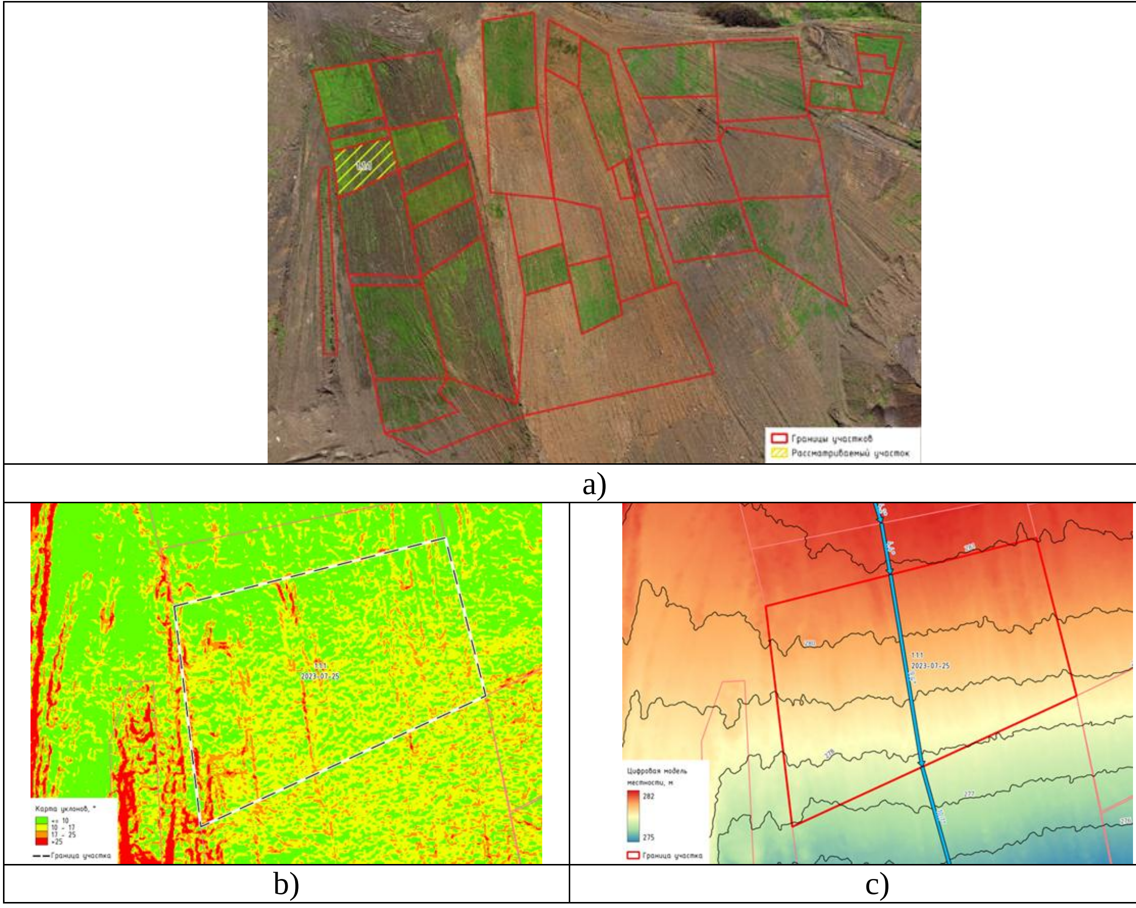
Development of geospatial materials (except for the intra-field slope map) was performed in the Agisoft Metashape Professional software package. The source materials for processing were photographic images, as well as coordinates and heights of the centers of projection centers of aerial photographs.

Accuracy control of the obtained geospatial materials was performed by control identifications in the program Agisoft Metashape Professional (Sheremetova 2016). The control of planned-high-altitude positions of control marks obtained as a result of photogrammetric processing was performed by the difference of coordinates and heights of marks on orthotransformed photos and their values obtained as a result of processing of satellite geodetic measurements. The RMS error of the coordinates and elevations determined for each control identification did not exceed 5.76 cm in plan and 5.23 cm in elevation for geospatial materials derived from RGB camera imagery and 7.1 cm in plan and 23.78 cm in elevation for geospatial materials derived from multispectral imagery.

On the basis of digital geospatial materials obtained as a result of desktop processing, the maps of experimental plots were formed (Mironov 2022). The maps aggregated all available key site parameters (crop name, planting date, growing season) as well as geospatially calculated parameters (NDVI values, slopes) over the entire period since planting date.

3. Results

The diagram of Site 1 is presented in Fig. 1.



a)

b)

c)

Figure 1: *The diagram of Site 1: a) overview diagram; b) digital terrain model with horizontals and average slope; c) map of in-field slopes*

Figure 1 shows that the average slope of the site is 9.4° and the elevation difference on the ground ranges from 275 to 282 meters. It should be noted that the total area of erosion-affected areas is small (Figure 2).

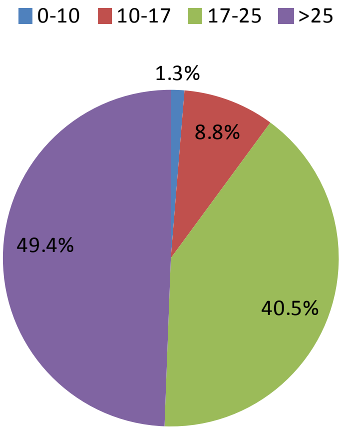
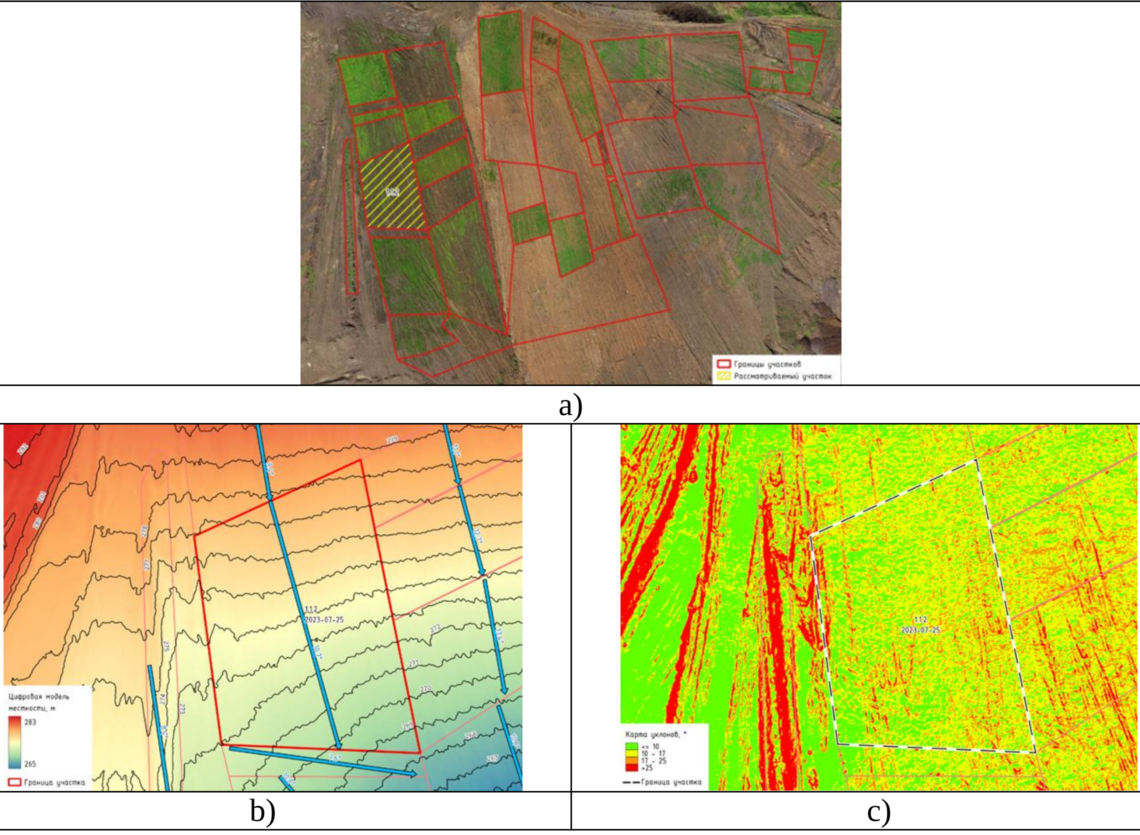


Figure 2: Diagram of intra-field slope distribution of plot 1

Thus, given that the area of the deepest areas of soil erosion is less than 10%, a negligible loss of projective cover can be predicted.

The diagram of Site 2 is presented in Fig. 3.



a)

b) c)

Figure 3: The diagram of Site 2: a) overview diagram; b) digital terrain model with horizontals and average slope; c) map of in-field slopes

As can be seen in Figure 3, the average slope of Site 2 is 10.7° and the height difference at ground level ranges from 265 to 283 m. The presence of a relatively flat surface after the leveling predicts a lower percentage of plant loss due to next season's flood events. The presence of erosive areas is due to the penetration of groundwater to the surface of the experimental area, with subsequent erosion of the upper soil layers. It should be noted that the total area of erosive areas is larger than at Site 1 (Figure 4).

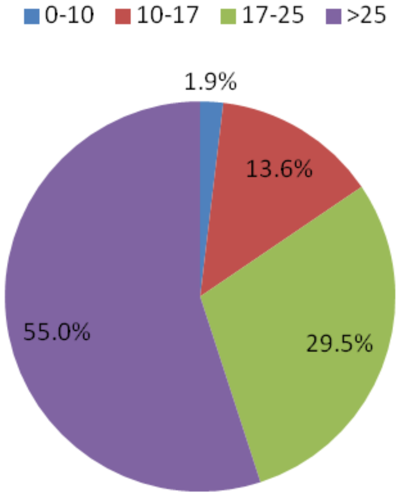
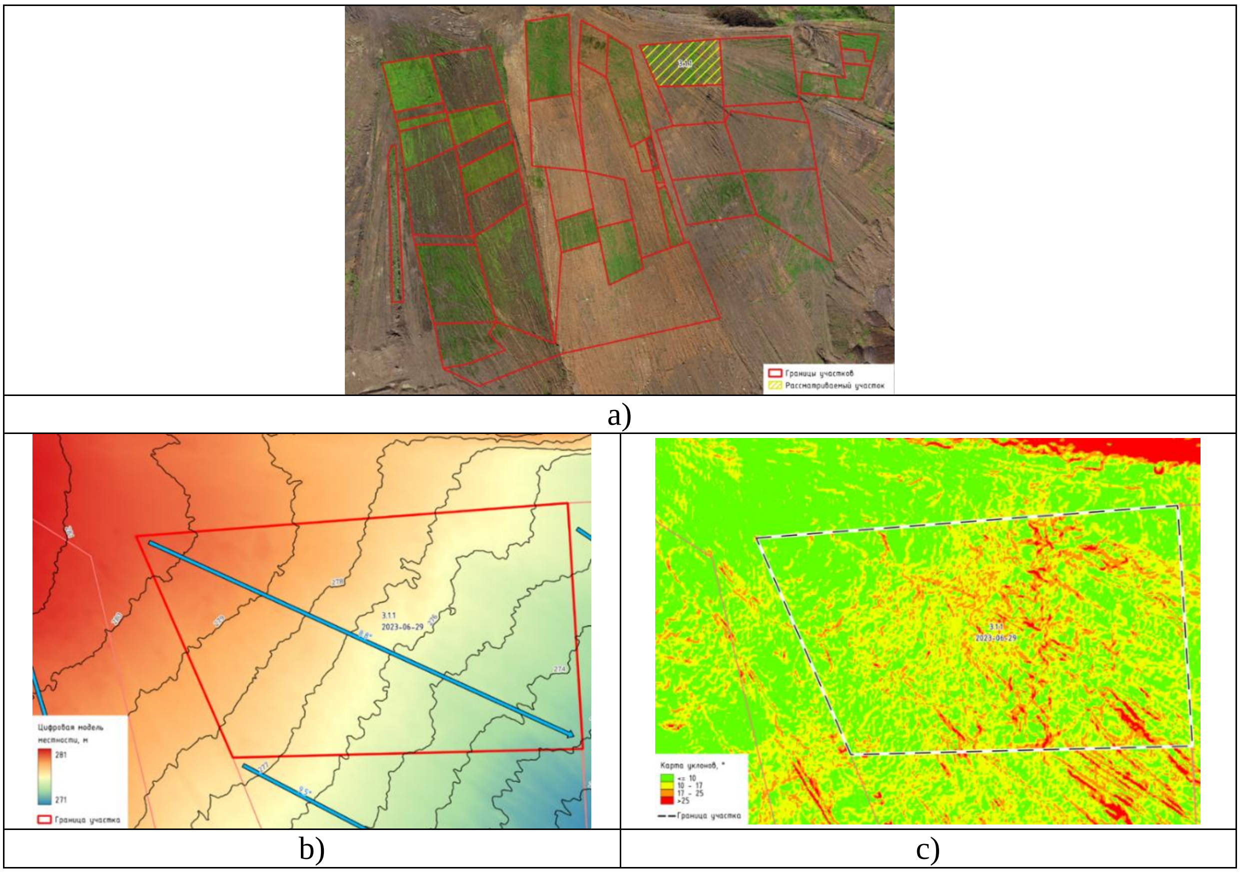


Figure 4: Diagram of intra-field slope distribution of plot 2

The area of soil erosion sites is about 15%, which predicts a minor loss of projective cover.
The diagram of Site 3 is presented in Fig. 5.



a)

b)

c)

Figure 5: The diagram of Site 3: a) overview diagram; b) digital terrain model with horizontals and average slope; c) map of in-field slopes

As shown in Figure 5, the average slope of the site was 8.8°, with ground elevations ranging from 271 to 281 meters. The presence of a relatively flat surface after the leveling predicts a lower percentage of plant loss due to next season's flood events. There are also areas of erosive process at Site 3 (Figure 5 (c)). The presence of these areas is due to groundwater infiltration into the surface of the experimental sector with subsequent erosion of the topsoil layers, as well as technical peculiarities of the surface layout in the absence of application of the top layer of PFSL. The area of erosion-affected areas accounted for 14% of the total sector area (Figure 6).

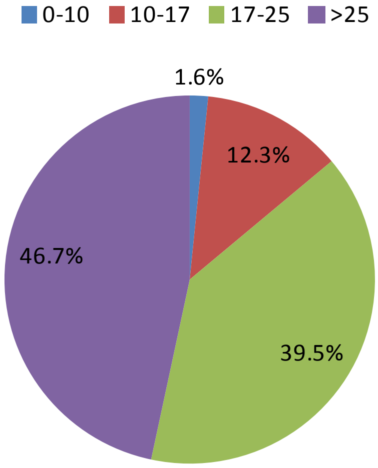


Figure 6: Diagram of intra-field slope distribution of plot 3

Based on the data presented above, it is possible to predict the loss of projective cover in the areas of the experimental sector subjected to erosive processes. Given the complexity of the remediation process, it is advisable to consider various innovative technologies as a decision-making tool when planning and implementing activities.
On the tenth day, seed germination energy was analyzed (Table 4).

Table 4: Determination of sowing qualities of seeds (laboratory germination)

Plant	**Class**	**Germination not less than, %**
Festuca rubra	III	85
Medicago sativa	III	70
Trifolium repens	II	90
Onobrychis arenaria	III	85
Agropyron cristatum	III	75
Pínus sylvéstris	I	90
Lárix sibírica	II	80
Bétula péndula	II	90
Rósa gláuca	II	80

The results of visual determination of plant survival ability in Plots 1-3 are presented in Tables 5-7 and Figures 7-9. Results were evaluated considering the introduction of the biobreparation to ½ of the total amount of planting and seeding material.

Table 5: General data on plant survival rate at Site 1

No. of rows	**Plants**	**Survival rate, %**	**Distance between plants in a row, m**	**Survival rate evaluation**
	Grass mixture with biopreparation	65		Good
	Grass mixture	75		Good
6	*Pínus sylvéstris*	70	2×2	Good
	Pínus sylvéstris with biopreparation	85	2×2	Excellent
4	*Pópulus nígra*	75	2×2	Good
	Pópulus nígra with biopreparation	85	2×2	Excellent
4	*Salix caprea*	65	1.5×1.5	Good
	Salix caprea with biopreparation	70	1.5×1.5	Good
3	*Caragána arboréscens*	50	1.5×1.5	Good
	Caragána arboréscens with biopreparation	55	1.5×1.5	Good
2	*Arónia melanocárpa*	40	1.5×1.5	Satisfactory
	Arónia melanocárpa with biopreparation	55	1.5×1.5	Good
2	*Berberis thunbergii*	75	1.5×1.5	Good
	Berberis thunbergia with biopreparation	80	1.5×1.5	Good

Table 6: General data on plant survival rate at Site 2

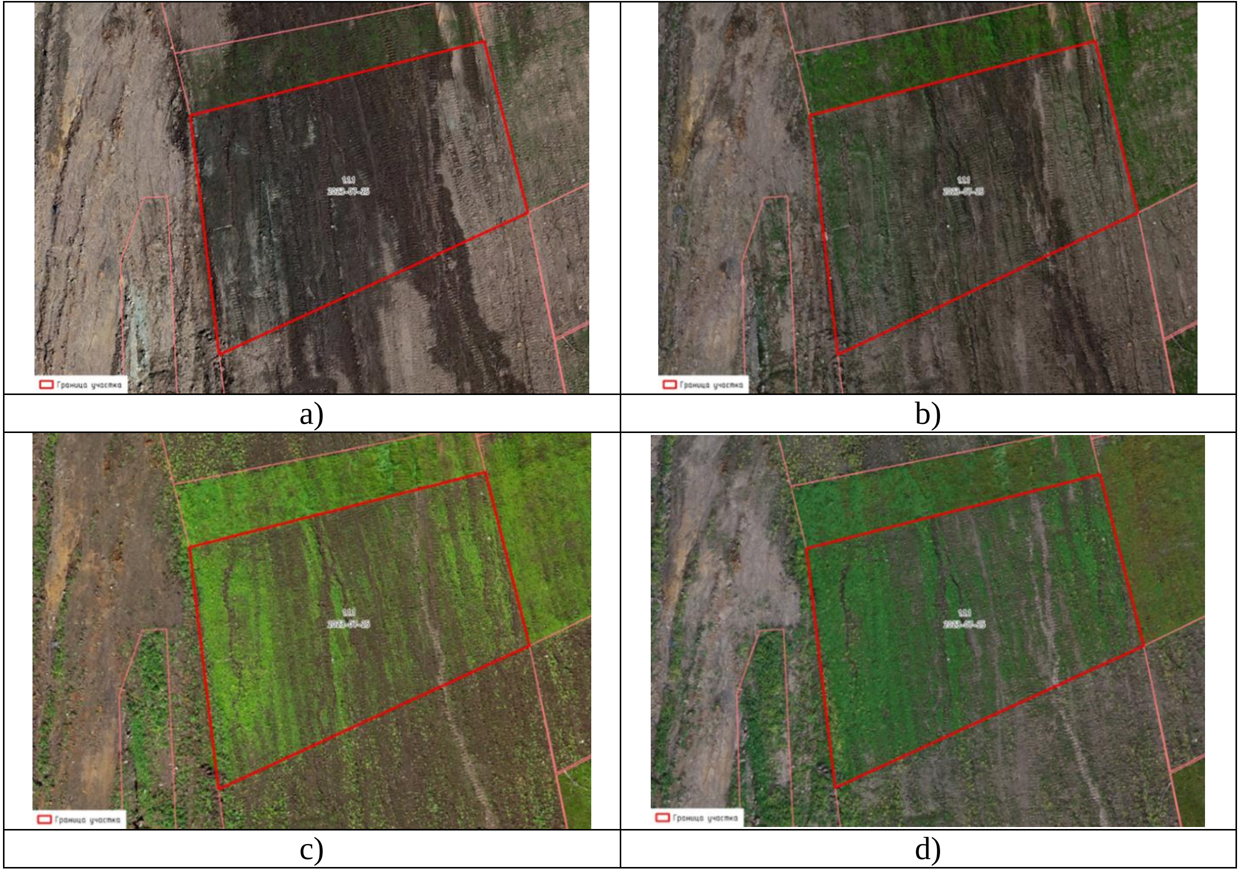
No. of rows	**Plants**	**Survival rate, %**	**Distance between plants in a row, m**	**Survival rate evaluation**
	Grass mixture with biopreparation	85	-	Good
	Grass mixture	70	-	Good
1	*Caragána arboréscens*	85	1	Excellent
	Caragána arboréscens with biopreparation	85	1	Excellent
2	*Ribes alpinum*	85	1	Excellent
	Ribes alpinum with biopreparation	85	1	Excellent
5	*Pínus sylvéstris*	55	1	Good
	Pínus sylvéstris with biopreparation	65	2	Good
1	*Pópulus nígra*	55	1	Good
	Pópulus nígra with biopreparation	55	1	Good
1	*Arónia melanocárpa*	45	1	Satisfactory
	Arónia melanocárpa with biopreparation	55	1	Good
2	*Berberis thunbergii*	50	1	Good
	Berberis thunbergii with biopreparation	50	1	Good
1	*Physocarpus opulifolius*	50	1	Good
	Physocarpus opulifolius with biopreparation	50	1	Good

Table 7: General data on plant survival rate at Site 3

No. of rows	**Planted species**	**Survival rate, %**	**Distance between plants in a row, m**	**Survival rate evaluation**
	Grass mixture hydroseeding	85		Excellent
	Grass mixture hydroseeding with biopreparation	85		Excellent
3	*Pínus sylvéstris*	65	1.5	Good
2	*Pínus sylvéstris* with biopreparation	70	1.5	Good
1	*Pópulus nígra*	75	1.5	Good
	Pópulus nígra with biopreparation	85	1.5	Excellent
1	*Caragána arboréscens*	85	1	Excellent
	Caragána arboréscens with biopreparation	85	1	Excellent
1	*Salix caprea*	75	1	Good

	Salix caprea with biopreparation	80	1	Good
1	*Arónia melanocárpa*	55	1	Good
	Arónia melanocárpa with biopreparation	70	1	Good
1	*Berberis thunbergii*	65	1	Good
	Berberis thunbergii with biopreparation	80	1	Good
	Ribes alpinum	80	1	Good
	Ribes alpinum with biopreparation	80	1	Good
	Lonicera dioica	85	1	Excellent
	Lonicera dioica with biopreparation	85	1	Excellent

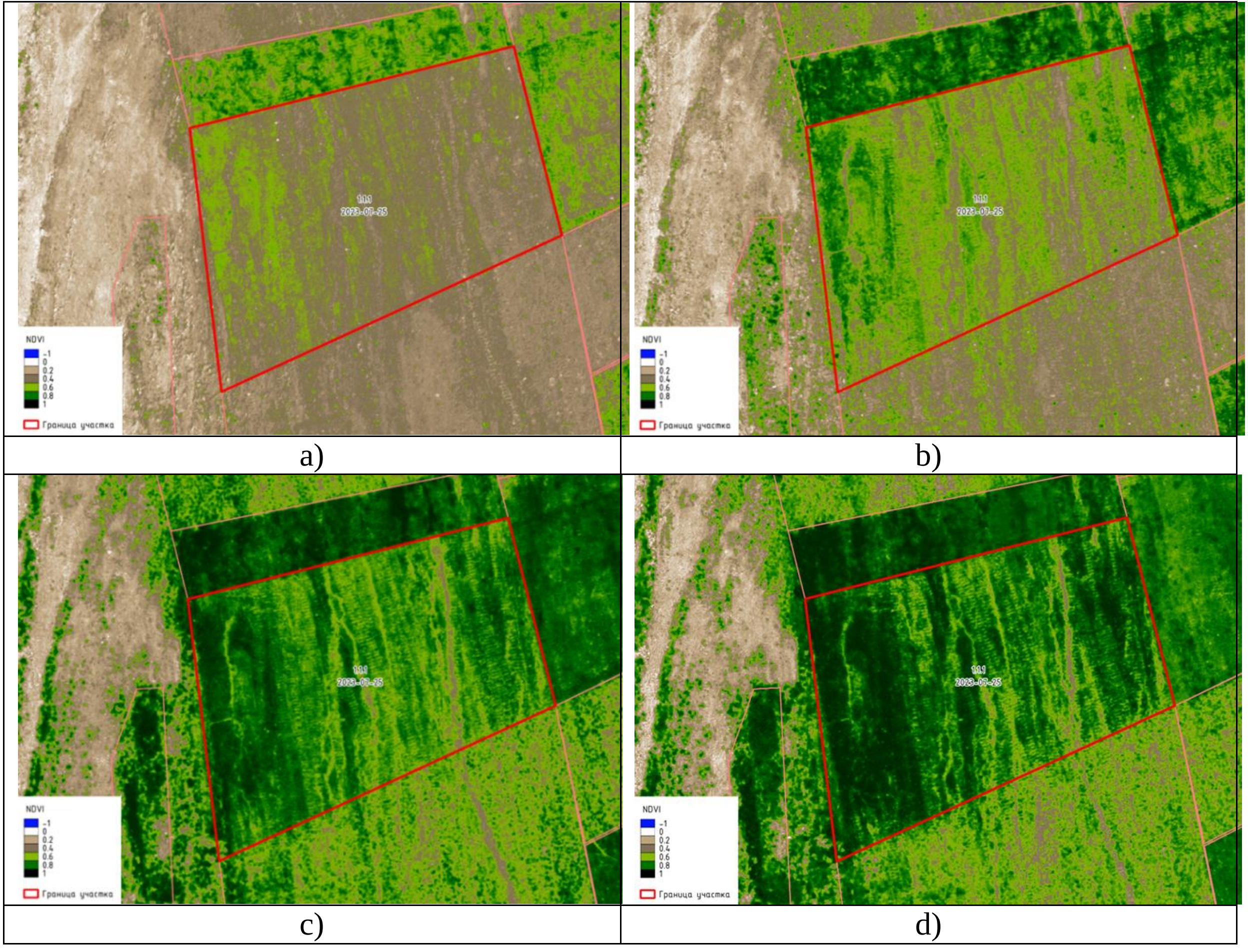
Figures 7-12 present the biomass dynamics of Sites 1, 2, and 3 in the visible range (orthophotoplan) and through NDVI index estimation.



a) b)

c) d)

Figure 7: Orthophotoplan of Site 1: a) as of 02.08.2023; b) as of 16.08.2023; c) as of 05.09.2023; d) as of 05.10.2023.



a) b)

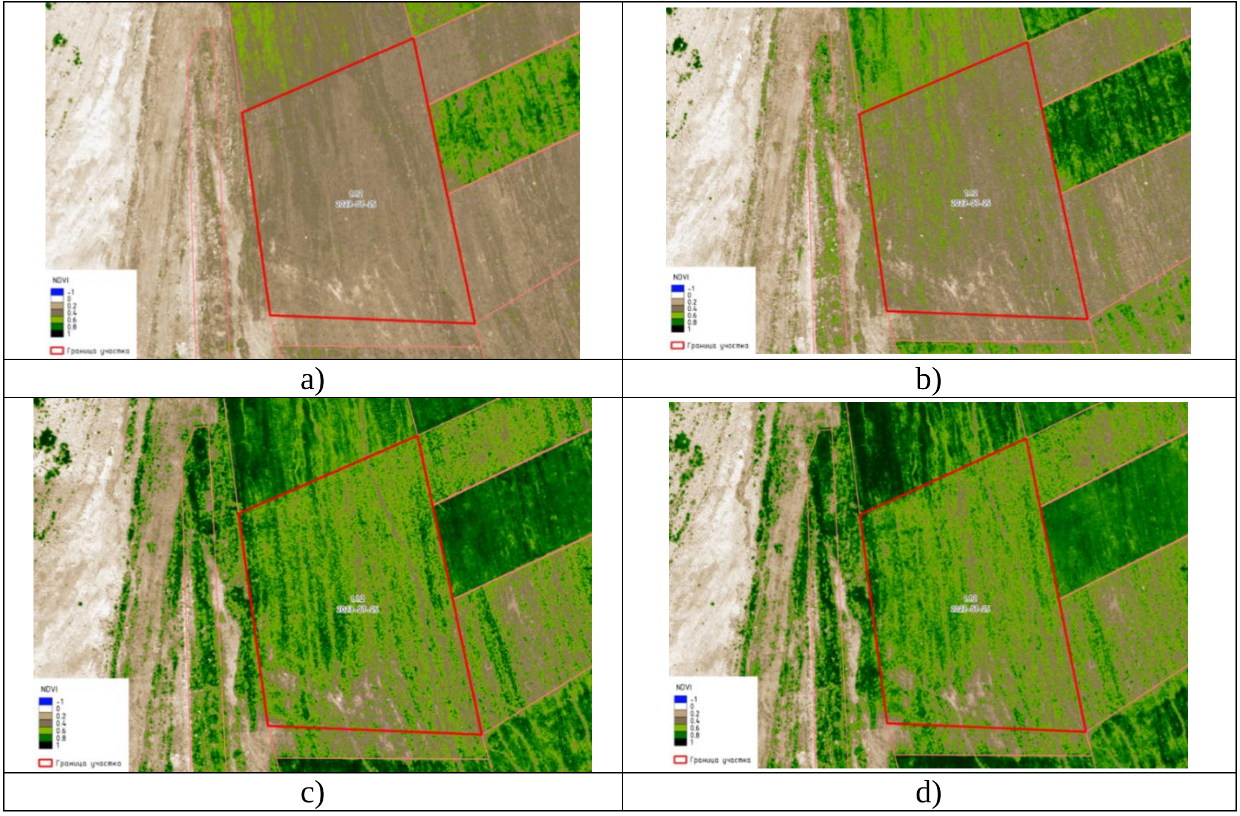
c) d)

Figure 8: NDVI vegetation index maps of Site 1: a) as of 02.08.2023; b) as of 16.08.2023; c) as of 05.09.2023; d) as of 05.10.2023.

a) b)

c) d)

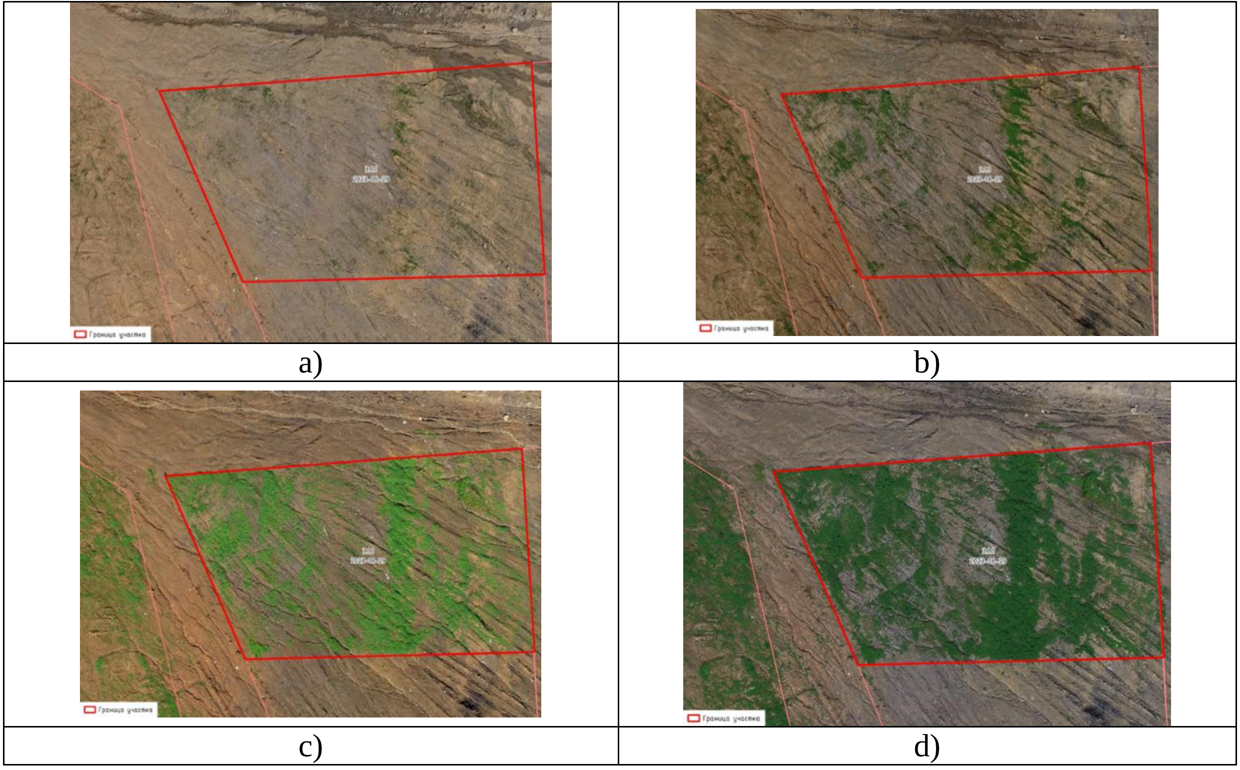
Figure 9: Orthophotoplan of Site 2: a) as of 02.08.2023; b) as of 16.08.2023; c) as of 05.09.2023; d) as of 05.10.2023.



a) b)

c) d)

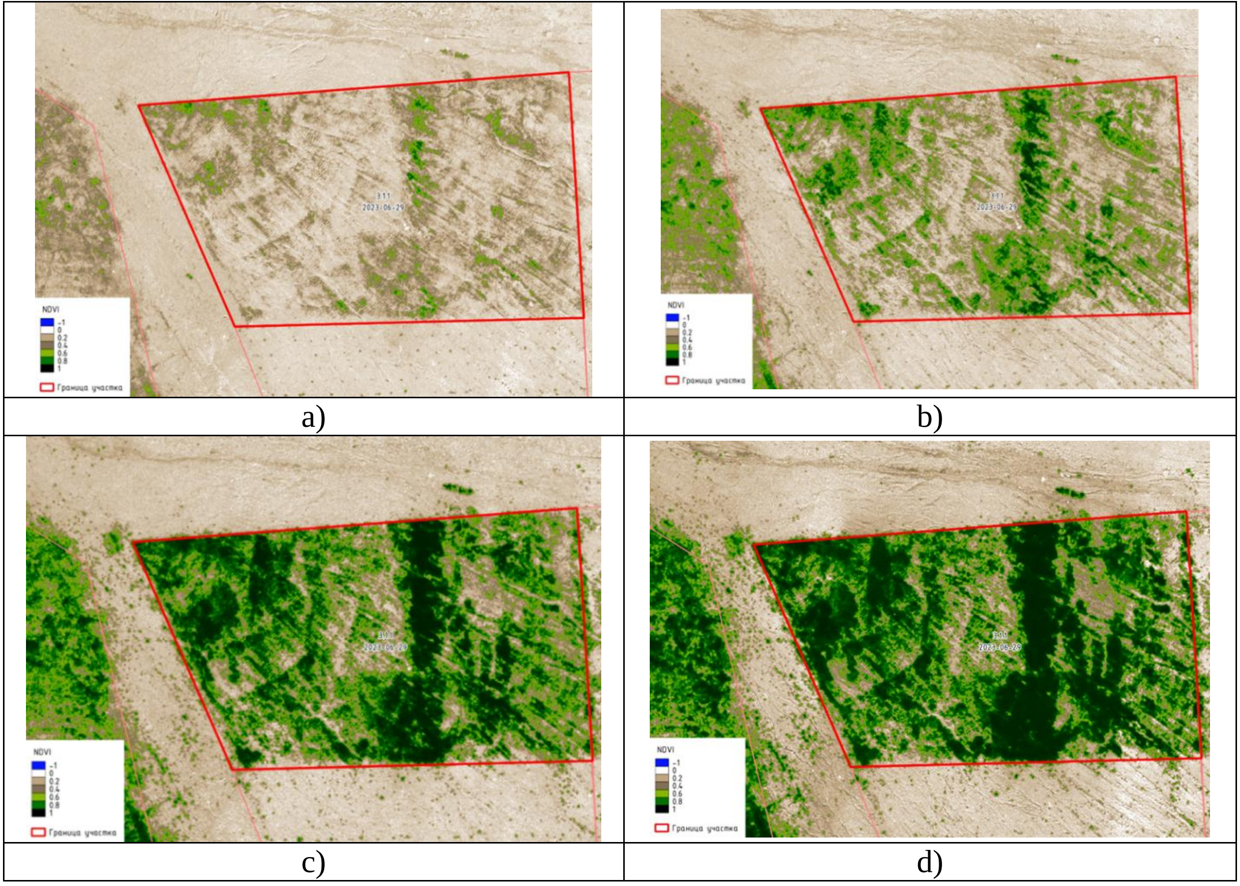
Figure 10: NDVI vegetation index maps of Site 2: a) as of 02.08.2023; b) as of 16.08.2023; c) as of 05.09.2023; d) as of 05.10.2023.



a) b)

c) d)

Figure 11: Orthophotoplan of Site 3: a) as of 02.08.2023; b) as of 16.08.2023; c) as of 05.09.2023; d) as of 05.10.2023



a) b)

c) d)

Figure 12: NDVI vegetation index maps of Site 3: a) as of 02.08.2023; b) as of 16.08.2023; c) as of 05.09.2023; d) as of 05.10.2023.

By comparing the orthophoto data in dynamics, it is possible to track the development of areas subject to erosion processes due to groundwater infiltration. Correlating the coordinates of such areas with NDVI index maps confirmed the hypothesis of projective area loss.

Nevertheless, sites 1, 2, and 3 show a positive trend in the NDVI index distribution (Figures 13-15).

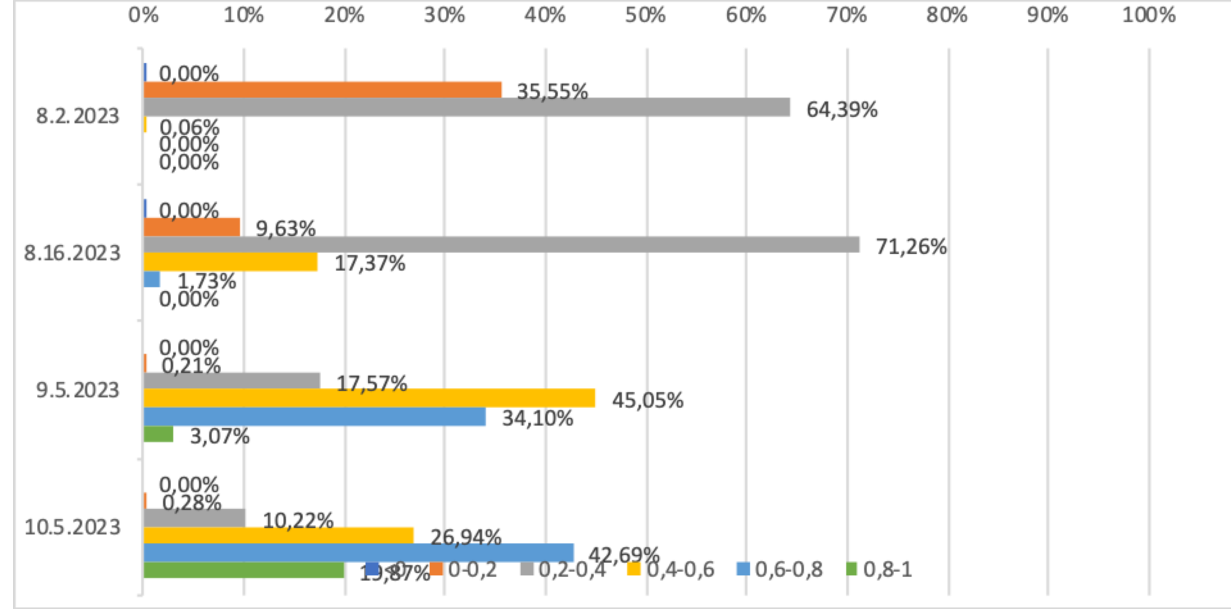


Figure 13: Dynamics of distribution of NDVI index values at Site 1

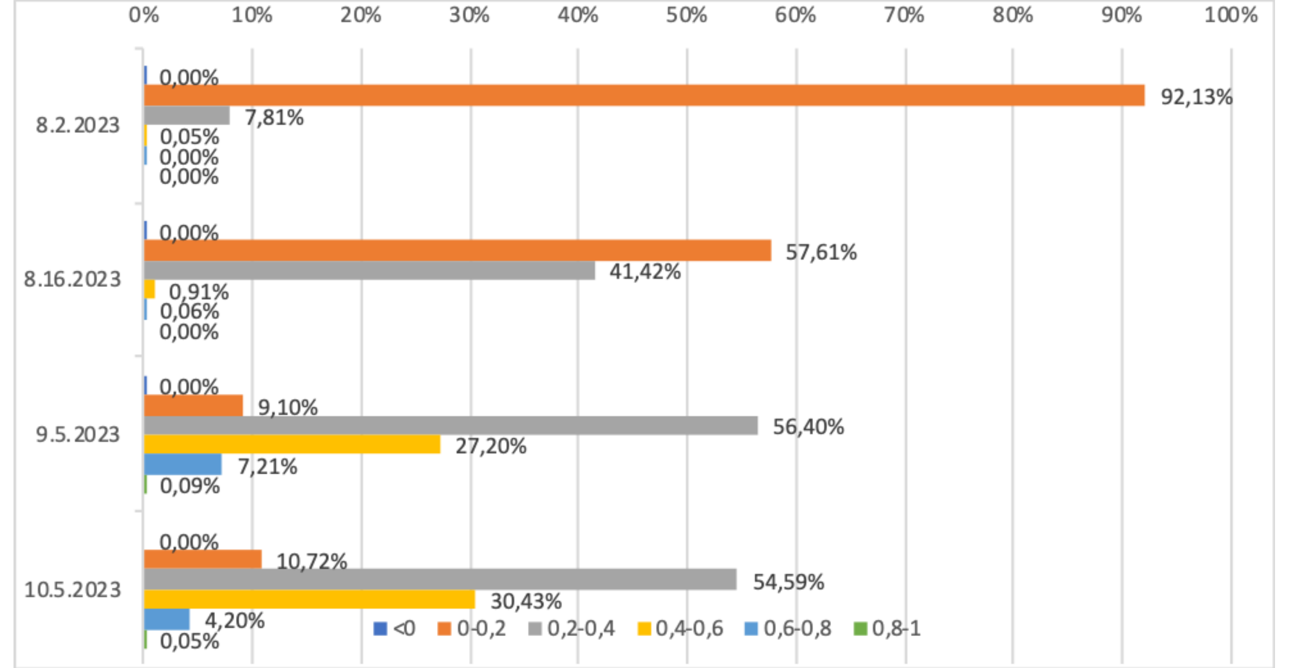


Figure 14: Dynamics of distribution of NDVI index values at Site 2

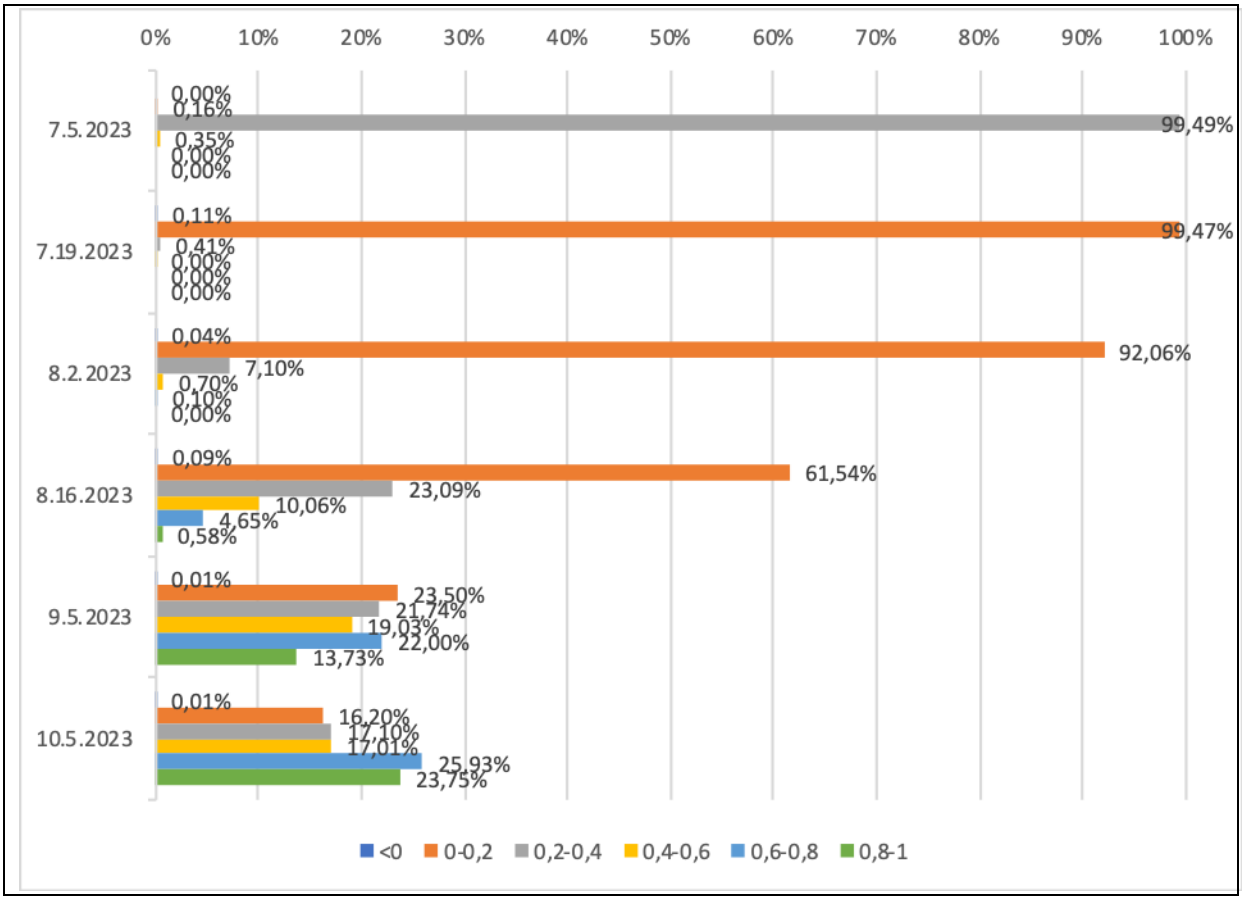


Figure 15: Dynamics of distribution of NDVI index values at Site 3

4. Discussion

At present, the application of geographic information systems (GIS) technologies is a promising approach for tasks involving a significant amount of spatial and attribute data. Geographic Information Systems (GIS) serve as tools for collecting, storing, analyzing, and forecasting information with full geographic visualization. GIS may include cartographic data, remote land sensing databases, digital elevation models, orthophotomaps, three-dimensional terrain models, and others. The application of this technology will provide an opportunity to comprehensively approach the tasks of land remediation.

For example, the article (Prokhorov, 2016) considers the advantages of GIS technologies for planning reclamation works: first of all, it is the reduction of financial costs and time for geodetic methods of building a digital terrain model (DTM). The DTM will allow the assessment of the actual condition of the site subject to remediation, the determination and systematization of the principal morphometric indicators of the territory, including area, depth, shape, excavation volume, slope steepness, and volumes of stone waste.

The study (Aksenova et al., 2017) examined the efficacy and necessity of employing three-dimensional computer graphics tools in the planning and forecasting of remediation activities. In the course of their work, a 3D model of the open pit mine was created in the exhausted area of the coal mine. Based on the model data, the volume and forms of earth surface disturbances were determined, and the required work plan for the technical stage of remediation was calculated. A photorealistic three-dimensional model of visualization of the planned results of remediation activities was also plotted. Based on the results of the study, the authors concluded that 3D modeling will eliminate errors at the stage of design and calculation of remediation measures.

NDVI is calculated from the absorption and reflection of red and near-infrared spectrum rays by plants and can be used to track the state of the vegetation cover of an area at a given point in time. This technology was used in one of the studies (Mikov *et al.* 2023). The NDVI index was used to analyze the condition of the vegetation at the study sites under remediation and to assess the current trend of restoration of disturbed lands.

The considered examples confirm the efficiency of GIS-technologies application in planning and control of remediation measures. The most promising method is three-dimensional modeling of the investigated area using data obtained by UAVs as the most accurate remote method of measuring geometric parameters. The program development should also take into account the need for the functionality of vegetation index calculation based on multispectral images for further control of the results of the measures. In addition, it is worth considering the specifics of the coal plant's exhaust areas.

The research was aimed at studying the germination, growth and viability of cereal-legume mixtures (clover, perennial ryegrass, alfalfa, fescue, ryegrass and wheatgrass) traditionally used for agricultural reclamation, depending on the soil quality (PFSL and FSL), as well as the application or introduction of different soil improvers: as organomineral fertilizer (sapropel); to conserve soil moisture (latex suspension), to accelerate soil-forming processes (microorganisms).

Analysis of Figures 1, 3 and 5 shows that the average slope of Site 1 is 9.4°, the ground elevation difference ranges from 275 to 282 m, the average slope of Site 2 is 10.7°, the ground elevation difference ranges from 265 to 283 m, the average slope of the site was 8.8°, the ground elevation difference ranges from 271 to 281 m.

The area of deepest soil erosion of Site 1 is less than 10%, Site 2 about 15%, Site 3 about 14% of the total area of the site, in this regard, the presence of a relatively flat surface after the planning works allows predicting a lower percentage of plant loss as a result of flood events of the next season, it is possible to predict a minor loss of projective cover.

The presence of erosive areas is due to the intrusion of groundwater to the surface of the test area, followed by erosion of the upper soil layers. It should be noted that the total area of erosion-affected areas is small (Figure 2).

The seed class determines the quality of the seed and its value. As can be seen from Table 4, the seed material intended for remediation varies within I - III classes, which indicates their quality and meets the requirements of GOST.

Table 5 demonstrates that 85% rooting rate was observed for *Pinus sylvestris* at Site 1. This can be attributed to the fact that this pine is a species that thrives in light conditions, exhibits rapid growth, and has minimal requirements for soil fertility. It grows on nutrient-poor and dry deep sands, on stony rubble, on chalk, sandy loam, loamy and even clay soils with different levels of humidity and fertility, due to the high plasticity of its root system. Pine is one of the most drought tolerant species. The wide ecological amplitude of the pine habitats makes it the most widespread tree species for reforestation of technogenic lands. All these indicators are conditioned by good adaptability of this species to industrially disturbed soils. Black poplar is a species that is not demanding in terms of growing conditions, especially soil fertility and moisture. All poplar species do not tolerate standing moisture well. Poplars are known to thrive in environments with ample light, a fact that becomes evident during the early stages of their growth and development. In the absence of sufficient light, they exhibit a notable reduction in their growth rate. With the addition of the biopreparation, poplar survival increased by 10% and showed good survival, as did the pine at this site. The lowest survival rate was observed in black chokeberry without the addition of the biopreparation. The selection of soil is not a critical factor for black chokeberry. This shrub grows equally well in both dry sandy and acidic soils. Nevertheless, black chokeberry prefers moist loamy soils. The main thing is that the soil should not be heavy. Since there was a drought at the time of planting, it caused the low survival rate of black chokeberry on this site. The addition of the biopreparation increased the survival rate by 15%.

The best germination of grasses on Site 1 was observed with the addition of biopreparation and amounted to 75%. The height of grasses without biopreparation was on average 10-12 centimeters, with the addition of biopreparation was on average 15-20 centimeters.

As demonstrated in Table 6, the survival rate at Site 2 was 85% for the following plants: Siberian Peashrub (*Caragana arborescens)* with and without biopreparation, and rosehip with and without biopreparation. *Caragana arborescens* is not demanding and grows quickly. Light-loving, but tolerates light shade. It has low requirements for soil fertility and moisture. The best development is achieved on sandy loam. In the other species, the survival rate ranged from 45 to 65 %.

Good species establishment was noted at Site 3. The rooting rate of more than 85% was observed for black poplar with biopreparation, Siberian Peashrub with and without biopreparation, and honeysuckle with and without biopreparation. Black poplar is a demanding plant in terms of growing conditions. When the biopreparation was added, the survival rate was 85%. When biopreparation was added, the survival rate increased in *Pinus sylvestris* and *Salix caprea* by 5%, *Arónia melanocárpa* and *Berberis thunbergii* by 15%. Plant survival rates of less than 50% were not observed at this site.

The survival rate of grasses with hydroseeding and with biopreparation was 85%. Hydroseeding provides an environment for rapid seed germination, protects the fertile layer from leaching and desiccation, and ensures uniform seedling growth. Grass height by the end of the growing season ranged from 12 to 25 centimeters and did not differ in height from plants planted with and without biopreparation.

Based on the data on the dynamics of NDVI index values in Sites 1, 2, and 3 (Figures 13-15), a systematic increase in biomass from the time of planting until the end of the growing season is evident. At the same time, the vegetation peak falls on the last day of the observations, i.e. the biomass growth of the grass mixture occurs until the end of the vegetation period, caused by the establishment of negative air temperatures and ground freezing. At the same time, the peak of vegetation on Site 1 with planting material (trees, shrubs) falls on an earlier period - in the last month of observations we can see a noticeable decrease in the area of dense vegetation. Significant biomass growth of Site 2 begins on 5.09.2023 and peaks by the time the growing season ends. This fact can be explained by long adaptation of plants of the sector associated with the establishment of high air temperatures and dry weather conditions at the time of planting. The peak of vegetation on Site 3 with planting material (trees, shrubs) is also on the last day of observation.

Our results are consistent with studies by leading scientists (Petrova and Rudzish, 2021; Serafimova and Stefanova, 2020; Babita *et al*. 2023; Hafez *et al.* 2023; Suleiman *et al.* 2021; Outbakat *et al.* 2022).

For example, Petrova and Rudzish (2021) described the role of soil improvers for bioremediation of disturbed land. It is shown that the use of organic (peat, sapropel, humus, forest litter, sawdust), mineral (limestone, dolomite, gypsum, glauconite, gypsum) and organomineral complex mixtures as soil improvers in the reclaimed territories of mining production allows to eliminate violations of water balance (salinization, dehydration, waterlogging), ratio of chemical substances, and also improves indicators of density, acidity and coefficient of soil loosening, providing optimal conditions of water, air, salt, nutrient and thermal regimes for planted plants.

It was also shown that remediation of land disturbed by mining operations includes the application of soil improvers. The application of such soil improvers is aimed at improving the physical and chemical properties of the soil, introducing nutrients, and stimulating soil fertility. It is necessary to choose the soil improver carefully, to control its characteristics and properties. For this purpose, a systematization of soil improvers used in the remediation of disturbed lands in the mining and processing complex is implemented. The main types of soil improvers are identified according to their genesis, composition, and action; land plots suitable for such reclamation approaches are described; and the process of soil remediation is demonstrated. It is also found that the main reasons for using new and unconventional soil improvers and soil improvement methods are low cost and prolonged effect.

This study by Serafimova and Stefanova (2020) considers the possibilities of biological remediation of soils contaminated with heavy metals using a soil improver – an organomineral mixture of sewage treatment plant sludge and ash from thermal power plants. Two species of herbaceous plants of the genus *Rumex, R. acetossela* and *R. patienta,* known for their ability to accumulate heavy metals, were selected for the experiment. The results of the study prove the possibility of using improvers for biological purposes.

In a study by Babita et al. (2023), organic fertilizers which include animal manure, biosolids, fruit pulp waste, paper mill waste, wood waste, crop residues, etc. are used for bioremediation. This review article explores the mechanisms by which organic additives alter soil physical, chemical, and biological properties with emphasis on fertilizer types and application rates for soil remediation and planted plant biomass production.

Suleiman et al (2021) used rhizosphere bacteria *Azospirillum brasilense* as soil improvers. The most important chemical and biological parameters after the application of microorganisms to industrially disturbed landscapes were analyzed every month for five months. The results of the experiment demonstrated that inoculation of *Azospirillum* increased soil organic carbon, dehydrogenase, and urease and introduced the required amounts of iron (Fe^{2+}), zinc (Zn^{2+}), manganese (Mn^{2+}), copper (Cu^{2+}), and boron (B^{+}), as well as nitrogen (N), phosphorus (P), and potassium (K). At the same time, the percentage of exchangeable sodium, pH, and alkalinity decreased by 75%, 12%, and 43%, respectively, compared to the initial conditions. Suleiman et al. (2021) demonstrated that the application of gypsum ($CaSO_4{\cdot}2H_2O$) and bioorganic fertilizers (a combination of organic materials such as compost and straw with the inoculation of beneficial rhizobacteria) can enhance the productivity of industrially disturbed soils. Gypsum supplies crops with sulfur to accelerate growth and yield by increasing the production of phytohormones, amino acids, glutathione, and osmoprotectants, which are vital activators of plant response to stress caused by salinization of industrially disturbed land. Bioorganic additives have been shown to improve organic matter and carbon content, nutrient cycling, porosity, water-holding capacity, soil enzyme activity, and biodiversity in such soils (Outbakat *et al*. 2022). In general, the integrated application of gypsum and bioorganic additives in plant cultivation in biological remediation of technogenically disturbed landscapes is a very promising strategy.

5. Conclusion

When comparing the orthophoto data of the sites, the development of areas susceptible to erosive processes due to groundwater infiltration and technical features of the surface layout was followed in a dynamic way. Correlating the coordinates of such areas with the NDVI index maps confirmed the hypothesis of projective loss in projective cover area.

The study of different biological remediation technologies allowed us to evaluate the effect of biological growth regulators on growth processes expressed by linear indices of the root system, the above-ground part of the vegetative sphere and the total plant length. The individual responses of the cultivated plant species used in the biological remediation of the site and their positive response to the use of pre-sowing seed treatment with biological growth regulators were determined.

The data collected from biological remediation sites using soil improvers will be subjected to further analysis with the objective of identifying the most effective technology for phytoremediation of disturbed landscapes in the context of pronounced erosion processes.

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