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THE QUESTION OF CHOICE BETWEEN RECULTIVATION AND REVITALIZATION OF MAN-DAMAGED LANDS

Abstract. The study employed an analytical method that made it possible to predict the impact of mining stages on changes to the quarry surface. At the same time, the principle was adhered to that the greater the change in the surface of technogenic areas within the quarry, the less expedient it is to return it to its original state. Attention is focused on the analysis of the possibilities of vegetating external dumps in the process of their formation and stabilization in open-pit mining conditions using the example of the deposits of the Kryvyi Rih Iron Ore Basin, as well as foreign experience. For this purpose, the characteristics of the deposits are described from the point of view of the volume of rock mass movement in the technological processes of the mining enterprise and the economic feasibility of returning the material in order to restore secondary ecosystems and achieve ecological balance on man-damaged lands. The principles of land revitalization planning in open-pit mining are determined as an alternative to high-cost mining and biological reclamation measures. The study substantiates principles for planning land revitalization in open-pit mining as an alternative to costly mining and biological reclamation. It is established that revitalization of man-made lands allows the activation of natural processes of restoring disturbed landscapes with minimal human intervention and achieving the goals of environmental safety of post-mining territories. Under conditions of high costs. Given the priority of environmental safety for mining reclamation and insufficient quality of its results, faster environmental effects can be achieved through revitalization of disturbed lands. For this purpose, the features of dump formation technologies are determined, which from the very beginning will create favorable conditions for the most effective revitalization of landscapes disturbed by mining.

The results obtained indicate that revitalization ensures faster achievement of environmental goals, reduction of environmental risks and reduction of financial and technological constraints in the post-mining period. Given the priority of environmental safety and sustainable development of industrial regions, revitalization of man-damaged lands is a more effective and adaptive direction of restoration compared to traditional mining reclamation.

Keywords: revitalization, disturbed lands, dump technology, stages of restoration, environmental risks, quarry.

1. Introduction

The intensive development of the mining industry, accompanied by large-scale withdrawal and transformation of land resources, leads to the formation of vast areas of technogenically disturbed land that remain environmentally unstable and socially unsuitable for use for long periods. In Ukraine, this problem is particularly acute in industrially developed regions, especially within the Kryvyi Rih Iron Ore Basin, where the areas occupied by quarries, dumps, and tailings storage facilities significantly exceed those of naturally restored territories. Every year, 7–8 thousand hectares are allocated for the needs of the mining industry, mostly from land previously used for agriculture or forestry [1].

For comparison, in Germany, open-pit mining had disturbed 1.765 million hectares of land by 2015. In the process, 888 million m³ of overburden were displaced. In the early 1990s, the level of reclamation did not exceed 50% of the disturbed area. Today, about 600 thousand hectares still remain disturbed [2].



Technological aspects of reclaiming land disturbed by open-pit mining in Ukraine received the greatest development in the 1950s–1960s. During this period, the main technological solutions concerning mining systems and technology of deposit development were substantiated, taking into account the need for land recultivation and for minimizing the extent of land disturbance associated with mining operations [3]. However, technological progress in this area has not solved the problems of high recultivation costs and the low quality of reclaimed technogenic land [4].

The low level of land recultivation leads to environmental risks in their subsequent use. To counteract technogenic risks, it is necessary to compensate for environmental damage caused by mining and to achieve a balance between economic interests and the environmental consequences of technological decisions [5].

The current environmental and land legislation of Ukraine obliges subsoil users to carry out mandatory recultivation of disturbed lands after the completion of mining operations. At the same time, long-term experience with mining recultivation demonstrates its high capital intensity, lengthy implementation periods, and limited effectiveness in restoring the natural productivity and ecological stability of technogenic landscapes. In many cases, even after decades, reclaimed lands fail to reach the parameters characteristic of undisturbed ecosystems, which reduces the economic feasibility of such measures and does not ensure the expected social benefits.

In study [6], an MCDM (Multiple-Criteria Decision-Making) model based on 12 criteria was applied to determine the optimal option for restoring the territory of an open-pit coal mine, representing the relevant subprocess systems of surface mining. The selected criteria encompass technical, technological, organizational, economic, social, and aesthetic aspects for evaluating the proposed recultivation solutions, i.e., integrated technological measures. Each criterion was assigned an appropriate weight coefficient. Based on the analysis of these criteria, a forestry-oriented approach to land restoration is proposed. The study identifies 20 potential zones for the restoration of disturbed lands to which the defined criteria may be applied. In addition, natural succession of disturbed land plots is considered as one of the restoration options. However, this study does not sufficiently account for the influence of overall dump-formation technology on the creation of favorable conditions for the recultivation or revitalization of technogenic lands.

Jiayin et al. [7] define land-restoration concepts following open-pit mining according to the geographical location and economic conditions of mining regions. Among the principal measures for rehabilitating technogenic lands are «baseline afforestation», «near-natural renaturation», «integration of agricultural and forestry practices», and «development of cultural tourism on abandoned lands». These approaches to land-restoration planning have been implemented in a project for the rehabilitation and integrated utilization of coal at an open-pit coal mine in Datong, Shanxi (China). It is noted that forested landscapes may be attractive for tourism and can generate additional economic benefits despite the absence of agricultural production.

Most approaches to land restoration in the mining industry involve creating vegetation cover on the soil surface that protects land from destruction caused by atmos-

pheric effects [8]. One of the most significant problems in the formation of technogenic landscapes is dust emissions from overburden if dumps have not been revegetated. If dumps undergo natural revegetation, it becomes possible to prevent the weathering of underlying rocks that are environmentally hazardous with minimal cost. In this case, plant species with economic value that can grow successfully in the relevant regions should be used.

When selecting tree species, their adaptive capacity for growth and development on spoil substrates, which are characterized by highly variable chemical and physical properties, is taken into account [9]. Although the area of the mining allotment is much larger than that of the quarry, the most intensive land transformation occurs within the quarry itself, and its restoration constitutes the major part of the work in any land recultivation or revitalization projects for areas disturbed by mining activities as a whole. Particular attention should be paid to dumps composed of rocks that are toxic to the environment [10]. Land revitalization should be aimed at restoring the disturbed ecological balance while at the same time creating opportunities in the post-mining period for the beneficial use of technogenic landscapes [11]. The study [12] notes that revitalization offers many promising directions for the use of technogenic lands—from habitats for biological species to forestry, recreation, and local tourism.

Study [13] outlines approaches to creating a fully functional landscape at minimal cost, achieved through reliable forecasting of changes in the natural-technical system and the use of natural self-restoration processes. At the same time, the development of secondary ecosystems is linked to the presence of water bodies at the quarry site; however, during the formation of a technogenic landscape, substantial areas emerge where vegetation cannot access the water resources located at the lowest point of the quarry. Therefore, it is necessary to consider options for moisture retention in the upper horizons of the technogenic landscape as well.

Under these conditions, there is growing scientific and practical interest in alternative approaches to the restoration of man-damaged territories, particularly in the concept of revitalization, which is based on the use of natural ecosystem self-recovery processes, taking into account their capacity for self-organization, successional development, and adaptation to altered environmental conditions. Revitalization does not involve mechanically reproducing the former state of the land; rather, it entails the formation of a new, environmentally stable and functionally valuable system integrated into the surrounding landscape and suitable for further socio-economic use.

Despite the existence of individual studies devoted to both recultivation and revitalization of man-damaged lands, methodological and criteria-based approaches for substantiating a choice between these two restoration pathways remain insufficiently developed in the scientific literature. Particularly important is consideration of how technological decisions in the formation of dumps and quarries influence the subsequent possibilities for ecological rehabilitation of territories, as well as comparative assessment of the environmental, economic, and social consequences associated with implementing different restoration scenarios.

In this regard, the relevance of this study is due to the need for scientific justification of the choice between recultivation and revitalization of man-damaged lands based on a comprehensive analysis of natural, technological, and socio-economic factors. The results obtained may serve as a theoretical and practical basis for improving the efficiency of managing disturbed areas in the post-mining period, reducing environmental risks, and ensuring the sustainable development of Ukraine's industrial regions.

2. Methods

The article employs an analytical research method that involves determining the impact of mining stages on changes in the quarry surface. It was assumed that the greater the alteration of the surface of technogenic areas within the quarry, the less feasible it is to restore it to its original state. The study focuses on analyzing the possibilities for greening external dumps during their formation and stabilization under open-pit mining conditions, using deposits of the Kryvyi Rih Iron Ore Basin as an example, as well as international experience. For this purpose, the characteristics of the deposits are described in terms of the volume of rock mass movement in the technological processes of a mining enterprise and the economic feasibility of its return for the purpose of restoring secondary ecosystems and achieving ecological balance on man-damaged lands.

The next stage of the study revealed the advantages of revitalization man-damaged lands in terms of improving the environmental condition of mining areas and reducing recultivation costs. The methodological approach to choosing between recultivation and revitalization of disturbed lands is based on assessing positive environmental changes in restored areas and on technological solutions enabling favorable conditions for land revitalization while simultaneously reducing the cost of recultivation land that fails to ensure the required quality of restored areas. The selection of a waste-dump formation method from the very beginning of deposit development should be aimed either at recultivation or at the revitalization of disturbed lands.

3. Results and discussion

Open-pit mining is one of the most intensive factors transforming the geological structure and land relief, forming man-made landscapes with a high degree of morphological heterogeneity. Such landscapes are characterized by significant elevation differences, diverse slope exposures, and a complex set of landforms that differ substantially from their natural counterparts. The most pronounced changes are observed in areas where mining operations are combined with overburden disposal zones. Exogenous geological processes undergo the most significant changes under the influence of technogenesis, which also affects the development of surface relief. External dumping of rocks and mineral processing waste in such areas contributes to the formation of a "mountain-like" technogenic relief. Thus, the trend toward a continuous acceleration of changes in the Earth's surface relief under the influence of technogenesis is currently dominant [14]. In the absence of special protective measures, such

landscapes remain environmentally unstable for a long time and pose increased environmental risks.

It has been established that when the depth of open pits exceeds 500 m, the area of waste dumps exceeds the area of the quarry by 4–5 times. The average quarry areas are as follows: 300–500 ha for building materials extraction, 1,000–1,500 ha for coal mining, and 2,000–3,000 ha for iron ore mining [15]. Such a scale of land disturbance leads to the formation of extensive technogenic territories requiring a long period of ecological stabilization.

An analysis of the spatial structure of the mining landscapes of the Kryvyi Rih Iron Ore Basin showed that the total area of quarries is about 4 thousand hectares; external and internal dumps – 6,200–7,000 ha; tailings storage facilities – 7,500 ha; industrial sites – about 3,000 ha; mines – 2,000 ha; and subsidence zones – 1,400 ha. More than 3 billion tons of beneficiation waste and 3.5 billion tons of overburden have been accumulated there. The basin currently operates seven open pits with depths reaching 300–500 m. There are 27 dumps – plateau-like terraced formations in the form of embankments 60–100 m high with slope angles of up to 40°, as well as four tailings storage facilities covering more than 7,000 ha, in which millions of cubic meters of technogenic sludge are stored [16].

It has been established that the technological process of dump formation in Kryvbas is determined by the steeply dipping type of deposit occurrence, as a result of which the majority of the overburden is placed in external dumps. According to design standards, waste dumps should be located (where possible) in areas unsuitable for agricultural use, on the periphery of enterprises, in accordance with zoning regulations for the placement of the production complex [17]. Dump formation represents the final stage in the technological chain of overburden operations and is characterized by its own specific technological processes. In general, the area of external dumps exceeds the area of the open pits themselves by approximately 1.67 times. External and internal dumps, together with tailings at the mining and processing plants storage facilities for mining waste, account for up to 80–95% of the total mining allotment area subject to revitalization or recultivation. Thus, the technology of dump construction plays a decisive role in their subsequent natural revegetation. It has been established that dump formation technology is a determining factor in the further ecological evolution of technogenic landscapes. In particular, bench geometry, slope aspect, and the degree of microrelief preservation directly influence the intensity of successional processes, the hydrological regime, and the stability of vegetation cover.

At the mining and processing plants of the Kryvyi Rih Basin (Kryvbas), the most widespread methods are excavator dumping with rail transport (68.7%) and bulldozer dumping with road transport (31.3%). The formation of excavator and bulldozer dumps with a design height of 120 m is carried out in 10–30 m benches, which are usually formed simultaneously over the entire allocated land area. The widespread use of this technological dumping scheme is explained by the low stability of the dump foundation. The bench-by-bench method of dump formation has caused intensive disturbance of land areas. Therefore, today most dumps in Kryvbas are developing through vertical expansion (increasing height). The width of berms between

benches in the working position ranges from 50 to 200 m, and in the final position from 20 to 50 m [14].

Technogenic facilities in Kryvbas affect all natural components of the environment. The use of fertile land for mining facilities, disturbance of the geological environment, chemical contamination of soils and alteration of their physical properties, air pollution, transformation and degradation of landscapes, and destruction of biota are the main causes of the critical condition of ecosystems and public health in Kryvyi Rih. An analysis of the environmental situation in Kryvyi Rih shows that effective measures have been developed to address most environmental degradation problems and improve environmental conditions.

As of 2003, the area of external dumps in Kryvyi Rih reached 70 km²; under otherwise equal conditions, dust generation in these areas exceeds wind erosion on ploughed land by 2–4 times [18]. However, there are no systematic anti-deflation measures at the dumps comparable to shelterbelts used in agricultural landscapes. Practice shows that the areas allocated for overburden dumps and tailings storage facilities significantly exceed those directly occupied by mining operations and industrial sites [19]. The ratio of external to internal dump areas in the Kryvyi Rih Iron Ore Basin ranges from 2:1 to 3:1. This confirms the decisive role of dump formation technology in shaping environmental conditions for the further restoration of man-damaged lands.

Naturally, a mining enterprise must carry out large-scale and costly activities aimed at protecting the surrounding area from production waste or removing such waste, improving the mined-out area, and restoring disturbed land. This involves addressing the following issues:

- 1) which quarry closure technology will be adopted;
- 2) how the mined-out quarry space, overburden dumps, tailings storage facilities, and other technological structures created for the development of the deposit can be utilized;
- 3) who will bear the costs of land restoration once the quarry, as an enterprise, ceases its production and business activities;
- 4) how the lands disturbed by open-pit mining will be restored in terms of area and quality.

Addressing these issues requires material, technical, technological, financial, and organizational support for the implementation of special measures. At present, such support is insufficient. This is because the restoration of vegetation cover on disturbed lands is carried out using conventional methods, such as recultivation. Recultivation is a comprehensive system of measures aimed at transforming technogenic landscapes in order to achieve ecological balance within a new natural–anthropogenic system and to create conditions for the intended use of restored areas in various sectors of the economy. As practice shows, the survival rate of planted vegetation on such lands is only 50–60%. Recultivation is a costly measure oriented toward the future economic use of land. Revitalization, in contrast, is considered a purposeful process of managing natural succession in technogenically disturbed areas, combining limited technical intervention with the activation of ecosystem self-

restoration mechanisms. This approach makes it possible to form secondary ecosystems adapted to altered physical and chemical environmental conditions.

In the Kryvyi Rih Iron Ore Basin, only about 10 thousand hectares of land have been reclaimed (out of 46 thousand hectares disturbed by mining operations), as shown in Table 1. Currently, the annual rate of recultivation in this basin is less than 1% of the total area of land disturbed by mining activities. During recultivation operations, surface leveling (grading) is carried out. However, this simplifies the structure of the soil and vegetation cover and equalizes habitat conditions, which significantly (for up to 20–50 years) inhibits the formation of natural ecosystems with a stable structure [14].

Table 1 – Areas of land disturbed by mining activities (as of 2003) [20]

Enterprise	Land allotment (ha)	Under open pits (ha)	Under waste dumps (ha)	Under tailings storage facilities (ha)	Under mines (ha)	Reclaimed in 2003 (ha)	Total disturbed land (ha)
OJSC «InGZK»	3985	550	536	978	535	16	2598
OJSC «CGZK»	5869	1061	422	2455	40	-	3938
OJSC «Southern GZK»	3916	652	1544	1527	-	30.8	3724
OJSC «Northern GZK»	7008	1538	1689	1975	-	7.3	5202
OJSC «Arcelor Mittal Kryvyi Rih» (Novokryvorizkyi GZK)	5285	607	1445	962	-	-	3438

One of the main reasons for this is that by the time quarrying is completed, the dumps are usually already formed in their final configuration, and funding for the recultivation of disturbed lands is often unavailable. Most areas disturbed by mining during the development of steeply dipping mineral deposits have a terraced relief, which technically and technologically complicates the implementation of traditional recultivation methods. Recultivation processes are costly and require considerable time for successful implementation. Therefore, recultivation works on external dumps of steeply dipping mineral deposits are currently rarely carried out.

On the external dumps of Kryvbas, the spontaneous restoration of ecosystems and vegetation lasts for a long period (up to 50 years). During this time, disturbed lands continue to negatively affect the environmental safety of surrounding areas. At the mining and technical stage of recultivation, dump surfaces are leveled. This further homogenizes habitat conditions for vegetation, thereby delaying the formation of natural ecosystems with a stable structure for extended periods.

According to Table 1, the share of dump areas within the total disturbed land area of quarries ranges from 10.7% to 42%. These areas form the basis for vegetation spread within the quarry under conditions of natural self-overgrowing. Technologically, the area of dumps can be increased through external dumping. This occurs as quarry depth increases and due to the technological impossibility of placing overbur-

den within the quarry area. Thus, the adopted mining system and the approved quarry depth determine the volume of overburden and, accordingly, the area of future external and internal dumps. The objective of technological measures under revitalization conditions is to shape dumps in a way that activates natural vegetation establishment processes and creates the most favorable conditions for their subsequent natural self-overgrowing.

If urgent measures are not taken to ensure the ecological safety of man-made landscapes, the consequences for the population and the environment may be quite unfavorable. Recultivation provides ecological benefits only after a long period of time, whereas revitalization through succession is a much faster process that allows the ecological goals of land restoration to be achieved within 5–12 years by creating favorable conditions for the natural revegetation of the surface.

The current costs of mining and technical land recultivation amount to about 250 thousand UAH per hectare when creating agricultural land with a bonitet score of 50–55, which is insufficient for efficient agricultural production. However, it is necessary to establish such dump slope angles that the risk of landslides and erosion caused by precipitation is minimized. The volume of preparatory work (in m³) required for revitalization does not exceed 15% of the volume of mining and technical recultivation work.

The need to invest significant funds without real returns, frequently unsatisfactory results of technogenic land restoration, and organizational problems have led to the actual cessation of mining and technical recultivation in the Kryvbas region. An analysis of its past results indicates that the main reason for its low efficiency is the attempt to create quasi-natural technosystems based on simplified formal models, which from the very beginning do not function as primary ecosystems.

Nature itself has mechanisms for solving the problem of land disturbance caused by mining operations; however, it is necessary to use technical means to create favorable conditions for restoration processes. First of all, it is essential to create barriers to the transfer of particles in the form of technological obstacles (anti-dust relief, water bodies, shields, mats, etc.) as well as vegetation cover. An ideal solution would be to cover the entire surface with vegetation. To achieve this, it is necessary to create optimal moisture conditions and ensure the supply of mineral nutrients.

Thus, the formation of secondary ecosystems is a technological management of natural processes of spontaneous vegetation development on disturbed technogenic lands. It can be carried out by methods of activation, initiation, acceleration, diversification, modification of development scenarios, and the so-called regeneration of subsystems. Therefore, a combination of technosystems and ecosystem influence occurs (Fig. 1).

The formation of secondary ecosystems includes a sequence of alternating technological and ecological stages: the presence of consequences of mineral extraction > technological prerequisites for the formation of secondary ecosystems > ecological regeneration of natural ecosystems > activation of secondary ecosystem formation > secondary ecosystems with target environmental parameters and minimal ecological risks.

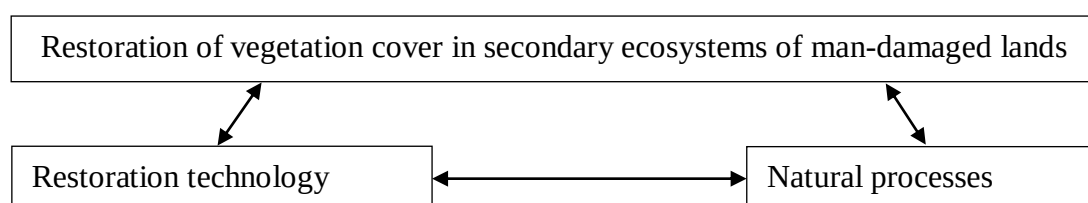


Figure 1 – Interaction of technological and natural systems in land revitalization processes

Within the framework of substantiating technological solutions for creating favorable conditions for the revitalization of technogenic landscapes, it is necessary to consider a technology for restoring lands disturbed by mining operations, which is aimed not at returning landscapes to their natural, original state, but at the formation of new secondary ecosystems. A technology that meets these requirements provides the implementation of three main tasks: adjustment of mining technologies, self-restoration, and activation of ecosystem development. The implementation of these tasks requires a clear scheme for identifying important environmental factors. The main factors that must be taken into account, and which are of primary importance in the process of activating ecosystem self-restoration in post-technogenic landscapes of the Kryvbas region, include landscape structure and relief features, water regime, solar energy, microclimatic characteristics, and soil-forming parent materials. These factors take into account hydro- and geochemical flows, as well as the physical and chemical features of the development of secondary ecosystems in technogenic landscapes.

Without targeted preparation for further use, technogenically altered lands remain a source of negative environmental impact for decades. Although in this case they are on the balance sheet of mining enterprises, and the latter, in accordance with the law, pay for the land they do not use, this does not lead to an improvement in the environmental condition of the territories. This is because these financial resources are distributed by state authorities without taking into account the source and nature of the damage, even though, by law, they should be used for land restoration. Thus, a situation arises in which there is no motivation to improve these territories or bring them into a usable condition (at least for some purposes), neither for the original owners nor for the mining enterprises that temporarily hold these lands on their balance sheet from the moment they are withdrawn from land use. Despite the fact that these lands are left unattended, secondary ecosystems gradually recover on them independently according to biological laws, and in some cases they are quite comparable in quality to natural ones. As a rule, nature does not tolerate emptiness and independently initiates biospheric mechanisms for the revival of life. Therefore, for the effective restoration of these lands, it is necessary to create protected areas, activate the processes of secondary ecosystem development, ensure their integration with natural elements of the ecological network, and enable their multifunctional use in the future.

In summary, we present the advantages of revitalization of lands disturbed by mining activities compared to conventional mining and technical recultivation (Table 2).

Table 2 – Comparison of factors affecting the effectiveness of recultivation and revitalization of the quarry area

Indicator	Recultivation	Revitalization
Process duration	25–70 years*	10–12 years
Environmental risks	>25%	<5%
Costs	250–280 thousand UAH /ha [20]	~50 thousand UAH /ha
Land mass deficit	Significantly limits the areas of recultivation	Does not limit the natural recovery process

Note: *depending on the way of recultivation

Therefore, if the goal of land conservation is primarily to achieve environmental objectives, revitalization will serve as a better alternative to land recultivation.

For the conditions of the Kryvyi Rih Iron Ore Basin, the projected duration for the formation of stable secondary ecosystems within the framework of revitalization is 8–12 years, provided that a favorable relief and water regime are created. For comparison, the implementation of mining and technical recultivation aimed at achieving functional ecological stability requires 25–50 years, depending on the intended land use.

Under conditions of revitalization of iron ore quarry areas, the intensity of the vegetation process will depend on the slope exposure of waste dumps, climatic conditions, the chemical and physical composition of the dumped materials, and the duration of the self-vegetation period. The process of natural revegetation of iron ore quarry dumps is illustrated by the example of Erzberg (Steiermark, Austria). Approximately 12 million tons of rock are extracted annually in the quarry, from which about 3 million tons of fine ore – siderite (FeCO_2), an iron-bearing mineral (~33.55% Fe) are produced.

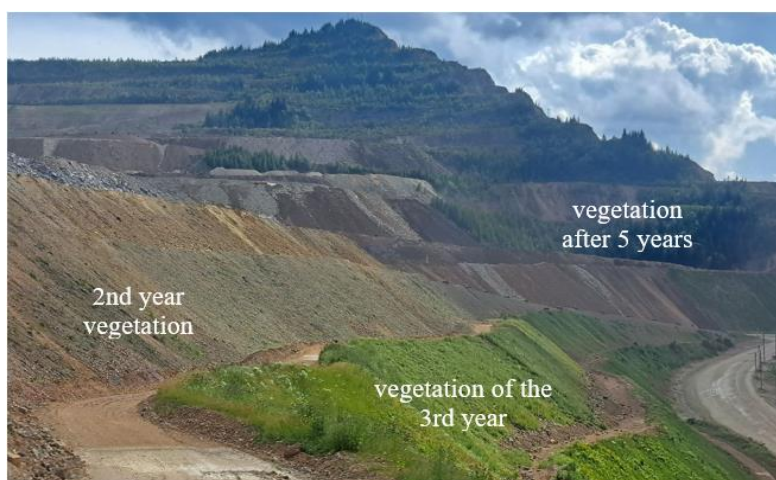
Freshly dumped waste heaps (Fig. 2a), as a rule, have underlying rocks on their surface that do not contain plant seeds. If artificial sowing of wild grasses is not carried out, natural vegetation spread will begin only in the second year (Fig. 2b). Using the Erzberg quarry as an example, one can observe the formation of fragmented vegetation during the second year, which begins to develop on the slope but does not yet provide full coverage of the entire slope area (Fig. 2b). In the following third to fourth year, the formation of a continuous vegetation cover can be expected, which fully covers the slope areas. Following grasses, shrub and tree vegetation will begin to develop on such dumps through natural succession (with a dominance period after the fifth year).

The implementation of the principles of sustainable development involves the integration of three key components – economic, environmental, and social. When addressing economic objectives, consideration must be given to resource conservation, reduction of anthropogenic pressure on the environment, and the creation of conditions for comfortable societal living.

The areas of dump revegetation shown in Fig. 3 represent overburden accumulation sites characterized by an increased risk of landslides; therefore, their greening is necessary both from the standpoint of geological safety and for activating natural restoration processes within the quarry area (Fig. 3).



a) newly formed external waste dumps of the quarry without initial vegetation (foreground)



b) external waste dumps of the quarry under conditions of natural revegetation

Figure 2 – Gradual natural revegetation of dump slopes at the Erzberg iron ore quarry, (Steiermark, Austria). Source: Autor's photo



Figure 3 – Satellite image of the Erzberg quarry, (Steiermark, Austria) [21]

The development project for mining operations at the Erzberg iron ore quarry is intended to ensure the further formation of overburden dumps in the form of benches to the north of the designated area. Thus, the revitalization territory will have a stepped configuration, with a gradual increase in elevation up to the highest point, where the formation of the dump complex will be completed. The natural revegetation of exhausted quarry areas will occur in stages, in accordance with the sequence of overburden deposition.

The restoration of disturbed ecosystems is an important focus of modern ecology, as the state of biotopes determines the preservation of biodiversity and the stability of natural processes. The article examines natural mechanisms of environmental self-recovery that enable the restoration of ecosystem functions without large-scale technical intervention. Then, three key aspects can be identified that characterize the effectiveness of such natural restoration:

- dynamics of ecological succession: natural ecological succession processes occur relatively quickly, even without human intervention. This means that the restoration of a biotope after disturbance proceeds gradually but effectively, involving local plant and animal species. The rate of succession allows the ecosystem to restore its functions and resilience within a comparatively short period of time;

- natural recultivation without engineering intervention: restoration processes do not require technical measures such as soil application, artificial planting, or other engineering methods. Natural recultivation demonstrates that an ecosystem is capable of self-recovery, provided that minimal conditions for the existence of living organisms are ensured;

- effectiveness of natural ecosystem revitalization: natural revitalization is effective, as biodiversity is restored, soil and hydrological characteristics improve, and the ecosystem gradually attains functional stability. This confirms that natural processes can ensure not only rapid but also high-quality restoration of disturbed landscapes.

Of course, the issue of potential loss of fertile soil during land revitalization remains debatable. However, this soil can be used to improve the fertility of other land plots or left on revitalized areas to stimulate natural vegetation regeneration processes. Thus, from the perspective of economic use, revitalized land areas in Ukraine would most likely be suitable for the establishment of nature reserves and, to a limited extent, for recreational purposes, provided that the terrain, safety conditions, and accessibility for the public allow it.

4. Conclusions

The study has shown that traditional mining and technical recultivation of lands disturbed by open-pit mining in the conditions of the Kryvyi Rih Iron Ore Basin is characterized by high capital intensity, long implementation periods, and limited effectiveness in achieving ecological sustainability of technogenic landscapes. In many cases, reclaimed areas do not acquire the properties of fully functional ecosystems and remain environmentally vulnerable for a long time.

The feasibility of applying revitalization as an alternative approach to restoring lands disturbed by mining activities has been substantiated. Unlike recultivation,

revitalization is based on the activation of natural self-recovery processes with minimal anthropogenic intervention and does not aim to restore the original natural state of the landscape. Instead, it focuses on the formation of secondary ecosystems capable of self-regulation and long-term stable functioning.

It has been established that the key factor determining the effectiveness of revitalization is the technological solutions adopted at the stage of dump formation. In particular, the creation of a terrain diverse in aspect and microrelief, the refusal of continuous surface leveling, as well as ensuring conditions for moisture retention in the upper horizons of the technogenic landscape contribute to the acceleration of successional processes, reduction of dust emissions, and mitigation of erosion.

A comparative analysis of recovery duration has shown that the formation of ecologically stable secondary ecosystems within the framework of revitalization in the conditions of the Kryvbas region is possible within approximately 8 – 12 years. Achieving a comparable level of ecological stability within mining and technical recultivation requires 25–50 years, depending on the intended subsequent land use. At the same time, the costs of implementing revitalization are 4–5 times lower compared to recultivation costs.

The obtained results indicate that revitalization ensures faster achievement of environmental goals, reduction of environmental risks, and minimization of financial and technological constraints in the post-mining period. Under conditions where environmental safety and sustainable development of industrial regions are prioritized, revitalization of man-damaged lands represents a more efficient and adaptive approach to restoration compared to traditional mining and technical recultivation.

Conflict of interest

Authors state no conflict of interest.

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ПІТАННЯ ВИБОРУ МІЖ РЕКУЛЬТИВАЦІЄЮ ТА РЕВІТАЛІЗАЦІЄЮ ТЕХНОГЕННО ПОРУШЕНИХ ЗЕМЕЛЬ

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Анотація. При виконанні досліджень в роботі використаний аналітичний метод дослідження, що дозволив передбачити визначення впливу етапів гірничої розробки на зміну поверхні кар'єру. При цьому дотримувалися принципу, що чим більша зміна поверхні техногенних ділянок в межах кар'єру, тим менш доцільним є її повернення до первісного стану. Увагу зосереджено на аналізі можливостей озеленення зовнішніх відвалів в процесі їх формування та стабілізації в умовах відкритих гірничих розробок на прикладі родовищ Криворізького залізничного басейну, а також закордонного досвіду. З цією метою описані характеристики родовищ з точки зору обсягів переміщення гірської маси у технологічних процесах гірничодобувного підприємства та економічної доцільності її повернення з метою відновлення вторинних екосистем та досягнення екологічної рівноваги на техногенно порушених землях. Визначені засади планування ревіталізації земель в умовах відкритих гірничих розробок як альтернативи високовитратним заходам з гірничотехнічної та біологічної рекультивативності. Обґрунтовані критерії, за яких в сучасних умовах господарювання необхідно здійснювати вибір на користь ревіталізації у порівнянні з іншими варіантами відновлення техногенних земель, які передбачають проведення гірничотехнічної рекультивативності. Встановлено, що ревіталізація техногенних угідь дозволяє активізувати природні процеси відновлення порушених ландшафтів за мінімального втручання людини та досягати цілей екологічної безпеки постмайнінгових територій. В умовах високих витрат на гірничотехнічну рекультивативність та недостатнього якісного рівня її результатів, більш швидкі екологічні ефекти можливо досягнути завдяки ревіталізації порушених земель. Для цього визначені особливості технологій відвалоутворення, які з самого початку створюватимуть сприятливі умови для найбільш результативної ревіталізації порушених гірничими розробками ландшафтів.

Отримані результати свідчать, що ревіталізація забезпечує швидше досягнення екологічних цілей, зниження рівня екологічних ризиків і зменшення фінансових та технологічних обмежень у постмайнінговий період. За умов пріоритетності екологічної безпеки та сталого розвитку промислових регіонів ревіталізація техногенно порушених земель є більш ефективним і адаптивним напрямом відновлення порівняно з традиційною гірничотехнічною рекультивативністю.

Ключові слова: ревіталізація, порушені землі, технологія відвалоутворення, етапи відновлення, екологічні ризики, кар'єр.