https://doi.org/10.33271/nvngu/2026-3/084

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VECTORS OF AUTOGENIC SUCCESSIONS OF VEGETATION IN A GRANITE QUARRY UNDER DRILLING AND BLASTING OPERATIONS

Purpose. To conduct a comprehensive analysis of the impact of drilling and blasting operations on the formation, structure, and dynamics of vegetation cover in quarry areas, using the Shamraivske granite deposit as a case study. This will make it possible to identify patterns of autogenic succession and vegetation self-recovery under conditions of long-term technogenic pressure and to assess the role of blasting operations as a specific ecological factor.

Methodology. The methodological framework of the study is based on field geobotanical methods, syntaxonomic analysis, and a synphytoindication approach. Geobotanical relevés were carried out on sample plots, followed by data processing in the software environments of Turboveg and JUICE using cluster analysis (TWINSPAN). Methods of synphytoindication were applied to assess environmental factors, the level of anthropogenic transformation, and the natural dynamics of vegetation. In addition, a hydrochemical analysis of the quarry's water bodies was performed.

Findings. It was established that drilling and blasting operations significantly affect the conditions of vegetation formation, determining the species composition, structure, and successional pathways of phytocenoses. The formation of derivative plant communities adapted to technogenic substrates and increased inputs of biogenic elements was revealed. It was shown that the combination of physical disturbance with chemical and hydrological changes can contribute to the acceleration of certain stages of autogenic succession.

Originality. For the first time, the possibility of using active granite quarries with regular drilling and blasting loads as model objects for studying vegetation dynamics under conditions of intensive explosive disturbance has been substantiated. The understanding of the role of blasting operations in shaping successional trajectories of quarry ecosystems has been expanded.

Practical value. The obtained results can be used for ecological assessment of quarry areas, forecasting vegetation self-recovery processes, substantiating reclamation measures and management of disturbed landscapes, as well as for extrapolation to other areas exposed to intensive explosive impacts, including those of technogenic and military origin.

Keywords: *drilling and blasting operations, quarry, vegetation cover, self-recovery, technogenic landscapes, autogenic succession, anthropogenic transformation, synphytoindication models*

Received: 16 January 2026
Accepted: 09 April 2026
Available online: 27 June 2026

Introduction. Intensive mineral extraction is one of the most powerful drivers of anthropogenic transformation of natural landscapes [1, 2]. Open-pit mining leads to radical alteration of relief, destruction of soil cover, transformation of the hydrological regime, and the formation of new substrates that significantly differ from zonal soils in their physical and chemical properties [3, 4]. As a result, processes of primary and secondary succession in such areas proceed according to atypical scenarios and largely depend on the characteristics of technogenic substrates, as well as on the type, intensity, and duration of anthropogenic impact [5].

Among mineral extraction technologies, drilling and blasting operations represent a specific and insufficiently studied factor influencing ecosystem dynamics [6, 7]. In addition to the mechanical destruction of rocks and soil horizons, explosions are accompanied by a complex of additional effects, including changes in substrate granulometric composition, vibration load, dust pollution, and the release of chemical reaction products into the environment [8, 9]. The combined action of these factors determines the conditions for vegetation formation, affects the structure of phytocoenoses, and sets the directions of their further successional development [10, 11].

Of particular scientific value are studies of vegetation self-restoration in quarry areas that have been operating for a long time and are subject to regular explosive loading [12, 13]. Such sites make it possible to trace how the combination of physical environmental disturbance with the continuous input of biogenic elements and changes in the water regime affects autogenic succession, the formation of derivative communities, and the stabilization of disturbed ecotopes. At the same time, quarries may be considered model analogues of territories disturbed by intensive explosive impacts of other origins [14], including those resulting from military activities [15, 16], or large-scale natural-anthropogenic disasters accompanied by severe disruption of soil and vegetation cover and alteration of biogeochemical cycles.

In this context, the study of vegetation dynamics within the sanitary protection zones of operating quarries becomes particularly relevant. Analysis of the structure and spatial organization of plant communities, as well as assessment of environmental changes caused by blasting operations, not only deepens understanding of the mechanisms of self-restoration of disturbed ecosystems but also contributes to the development of scientifically grounded approaches for forecasting and managing recovery processes under conditions of prolonged anthropogenic pressure.

At the same time, despite the growing number of studies devoted to the environmental consequences of mining activities, the issue of an integrated assessment of the impact of drilling and blasting operations on autogenic vegetation succession remains debatable and methodologically complex. The mechanisms of interaction between physical substrate disturbance and hydrochemical as well as biogeochemical environmental changes, along with their long-term effects on the rate and trajectories of phytocoenosis self-restoration, have not been sufficiently elucidated. Particular attention should be given to establishing cause-and-effect relationships between the intensity of explosive loading, the transformation of edaphotopes, and the formation of stable or, conversely, degraded plant communities. This underscores the need for comprehensive field and analytical research aimed at identifying patterns of successional vegetation dynamics under prolonged technogenic pressure and developing scientifically substantiated approaches for forecasting recovery processes in quarry ecosystems.

Literature review. Restoration of anthropogenically disturbed territories is one of the key challenges of our time. Increasing the area of natural vegetation through post-disturbance recovery provides humanity with a wide range of critically important ecosystem services [13]. Above all, this concerns mitigating the consequences of global climate change, enhancing biodiversity indicators, and restoring ecosystems damaged by military actions.

Vegetation recovery at mining sites is characterized by a number of specific ecological and engineering features. The most significant problem is the absence of fertile soil and the presence of reclamation substrates (technosols) with extremely unfavorable physical and chemical properties [1]. When explosives are used for rock fragmentation, several additional specific parameters arise. As a result, blasting operations, which are the primary method of extracting crushed stone and rubble materials, further influence the vectors of vegetation dynamics [6]. Changes in granulometric composition become particularly evident. Explosions generate a large proportion of fine fractions that may form a dense, impermeable crust (concretions) on the surface or, conversely, produce large unstable fragments [7]. Continuous vibrations can further hinder the formation of stable root systems and soil microbiological communities in adjacent areas. At the same time, significant amounts of dust and chemical reaction products are released into the atmosphere during explosions [8]. Dust deposition on plant surfaces slows photosynthesis, while chemical compounds dissolve in water and alter the chemical composition of edaphotopes in newly formed ecosystems [9].

Quarry landscapes create conditions highly similar to those arising after intensive military impact: destruction of soil cover, complete transformation of microrelief, and frequent exposure of parent material, including rocky substrates [14]. The primary similarity lies in the restructuring of the system of edaphic factors. The surface becomes deficient in organic matter, water-holding capacity decreases, and pH changes, all of which critically affect natural succession processes. Additionally, the environment utilized by biota becomes saturated with decomposition products of explosives [15]. Using quarries as examples, it is possible to observe how pioneer plant species gradually colonize and stabilize disturbed substrates, analogous to vegetation recovery processes in shelled territories. Modeling makes it possible to investigate the rate of primary soil layer formation and to identify the most stress-tolerant ameliorative species capable of rapid biological reclamation. Analysis of vegetation dynamics vectors in quarries that have remained at different stages of recovery for decades provides valuable empirical data on the long-term ecological consequences of intensive disturbance [3]. Thus, studying such sites offers a predictive model for developing effective and economically justified algorithms for restoring natural ecosystems affected by military actions [2].

Since plants obtain mineral nutrients from aqueous solutions, the presence of dissolved salt ions in water bodies correlates well with their availability to biota. The analysis of substances dissolved in soil substrates can only be linked to plant representatives that are entirely dependent on them. Many aquatic autotrophs, as well as species inhabiting rocky substrates, acquire these substances from water solutions not directly associated with soils. Therefore, modeling the influence of substances formed during explosions and subsequently dissolved in various water bodies on vegetation dynamics vectors becomes particularly relevant [17]. This primarily concerns compounds that serve as carriers of essential mineral nutrients or act as potent toxins for plants [4].

Unsolved aspects of the problem. Despite the substantial body of research devoted to vegetation recovery in areas disturbed by mining, the combined impact of drilling and blasting operations on phytocoenosis dynamics remains insufficiently studied. Most available works address the general condition of vegetation cover or the effectiveness of reclamation measures, whereas the specific effects of factors associated with regular blasting are considered only fragmentarily.

The role of explosive residues in shaping the chemical composition of substrates and quarry water bodies also remains unclear, particularly with regard to their influence on the availability of nitrogen compounds and the vectors of autogenic succession. Spatial differentiation of plant communities within sanitary protection zones, taking into account microrelief and hydrological conditions, has been investigated only to a limited extent, as have the possibilities of applying synphytoindication approaches to assess natural dynamics and anthropogenic transformation of ecosystems under prolonged blasting pressure.

Purpose. The aim of this study is to examine how the complex of factors induced by drilling and blasting operations affects the vectors of vegetation self-restoration dynamics. To achieve this aim, the following objectives were set:

- to classify plant communities within the sanitary protection zone of the Shamraivske granite deposit;
- to determine the features of spatial distribution and structural organization of plant communities depending on environmental conditions;
- to identify the main changes in abiotic environmental factors caused by drilling and blasting operations;
- to analyze how these changes influence the vectors of vegetation dynamics and successional development.

Methods. The study was conducted in 2025 within the sanitary protection zone of the Shamraivske granite deposit. The research materials included geobotanical relevés of plant communities and the results of a hydrochemical analysis of quarry water bodies.

For the geobotanical description of the model area, environmental characteristics were recorded and the cover of higher vascular plants was estimated using a modified five-point scale based on the Braun–Blanquet method, obtained by transforming the classical seven-point Braun–Blanquet scale [18]. Species cover values were assigned as follows: >75 % = 5 points; 50–75 % = = 4 points; 25–50 % = 3 points; 5–25 % = 2 points; and <5 % = 1 point. Thus, the Braun–Blanquet categories "1 point", "+", and "r" were all assigned the value "1 point" in the new scale.

The territory was divided into 25 × 25 m squares. Within each square, visually homogeneous patches showing features of particular syntaxa of plant communities were delineated. A geobotanical relevé was made for each patch. Forest vegetation plots covered at least 25 m^2 for young secondary forests and 100 m^2 for mature forests of any type; meadow plots were 2 × 2 m; and shrub plots were 10 × 10 m. Plot configuration was adjusted according to visual boundaries defined by dominants in each layer, the proportion of biomorphs, and the age structure of species groups.

Coordinates of relevés were recorded using a GPS navigator, and slope aspect and steepness were determined using the mobile applications "GPSTest" and "Clinometr".

A database of geobotanical relevés was created using Turboveg for Windows 2.0 [19]. Relevés compiled in Turboveg were exported to JUICE 7.1.29 as XML table files. Using the integrated JUICE module TWINSPAN, the relevés were grouped into clusters based on their fidelity in the synoptic table.

Environmental factor values, the natural dynamics index, and the integrated anthropogenic transformation index were calculated using synphytoindication methods. Environmental factors were assessed using the unified Didukh–Pluta scale database [20]. Anthropogenic pressure was determined using "EcoDBase 5d" database with the 18-point Didukh–Khomiak scale [21]. The natural dynamics index was described using a 21-point synphytoindication scale developed at the Laboratory of Ecosystem Theory, Zhytomyr Ivan Franko State University. Synphytoindication indices were calculated using Simagrl 1.12 [22]. The program's basic algorithm is based on Ramensky's formula and uses species cover values and data on their anthropotolerance stored in the "EcoDBase 5d" database.

Plant communities were identified using blocks of diagnostic species provided in the Prodromus of the Vegetation of Ukraine [23]. Names of higher vascular plant species follow Vascular Plants of Ukraine: A Nomenclatural Checklist [24].

Water analyses were performed by the certified measuring laboratory LLC "ECO-MB" (certificate No. 004-1/2024). Samples were taken from the sump, the settling pond, and the point where water is discharged into the Rostavytsia River. The analyses employed a pH meter zR-150MI, electrode ESK-10603, laboratory scales WAA60/X, a KFK-2 photoelectric concentration colorimeter, and a burette.

Findings. According to the level of anthropogenic impact on habitats and the degree of ecosystem transformation, the study area can be divided into three zones. The spatial distribution of these zones reflects a gradient of decreasing technogenic pressure and a simultaneous increase in the role of natural successional processes. Along this gradient, a consistent shift in environmental conditions is observed – from extreme technogenic ecotopes with disturbed edaphotopes to relatively stabilized natural valley-type biogeocenoses. This allows the quarry's sanitary protection zone to be considered a model testing ground for studying different stages of autogenic succession under differentiated anthropogenic influence.

The first zone includes areas experiencing constant and intense anthropogenic impact: sites of granite extraction, transport routes for mined material, and locations of technological facilities supporting extraction. Ecosystems in this zone are maximally transformed, and vegetation is at the earliest successional stages. Here, anthropogenic transformation indices exceed 15 points across most of the territory, while the natural dynamics index drops below 2 points. These values indicate a critical level of ecotope disturbance, at which natural ecosystem self-regulation mechanisms are virtually nonfunctional. Vegetation cover forms mainly through the random input of diaspores and is characterized by high instability, fragmentation, and short persistence of individual cenopopulations.

The second zone comprises areas where complete human transformation occurred in the past and where natural vegetation recovery processes now prevail over ongoing anthropogenic impacts. These include quarry elements that had not been exploited for more than one season at the time of survey. Within these sites, a transition from pioneer-ruderal to sod-grass and shrub stages of autogenic succession is already evident. Total plant cover increases, vertical structure becomes more complex, and processes of organic matter accumulation and soil formation intensify.

The third zone includes territory where natural ecosystems have been preserved but are exposed to anthropogenic influence largely unrelated to granite extraction. This zone encompasses elements of the Rostavytsia River valley: the channel, floodplain, and the first and second above-floodplain terraces. The presence of relatively intact natural biotopes within the study area plays a crucial role in forming the seed bank and ensuring continuity of successional processes on disturbed plots. These ecosystems act as donor centers of floristic diversity for technogenic quarry ecotopes.

The vegetation and biota of the study area are typical of the northern Right-Bank Forest-Steppe. They have formed under anthropogenic factors of varying intensity and type, as well as under processes of vegetation self-restoration in disturbed habitats. The combination of zonal and synanthropized floral elements creates a specific floristic complex characteristic of technogenically transformed forest-steppe landscapes. Its structure simultaneously includes native, apophytic, and alien species, reflecting multidirectional successional vectors. The plant communities of the study area belong to 20 classes, 31 orders, 48 alliances, and 97 associations (Table 1).

The obtained syntaxonomic diversity values indicate a high degree of vegetation mosaicity and the complexity of successional structure in the study area. The substantial representation of both pioneer and climax communities confirms the simultaneous functioning of successional series of different ages, resulting from the combination of long-term technogenic disturbance and natural self-restoration processes.

Table 1

Phytocoenotic diversity of the sanitary protection zone of the Shamraivske granite deposit

Class	Number of syntaxa		
	Orders	Alliances	Associations
Lemnetea de Bolós et Masclans 1955	1	1	2
Potamogetea Klika in Klika et Novak 1941	1	3	8
Phragmiti-Magnocaricetea Klika in Klika et Novak 1941	4	6	12
Molinio-Arrhenatheretea R.Tx 1937	3	6	16
Calluno-Ulicetea Br.-Bl. et Tüxen ex Klika et Hadač 1944	1	1	1
Trifolio-Geranietea Th.Müll 1962	2	4	6
Sedo-Scleranthetea BR.-BL. 1955	1	2	4
Epilobietea angustifolii Tx. et Preising ex von Rochow 1951	1	2	3
Robinietea Jurco ex Hadac et Sofron 1980	2	5	8
Vaccinio-Piceetea Br.-Bl. in Br.-Bl. et al. 1939	1	1	1
Carpino-Fagetea Jakucs ex Passarge 1968	1	2	4
Salicetea purpurea Moor 1958	1	1	4
Alnetea glutinosae Br.-Bl. et Tüxen ex Westhoff, Dijk et al. 1946	1	1	2
Franguletea Doing ex Westhoff in Westhoff et Den Held 1969	1	1	1
Stellarietea mediae R.Tx., Lohmaer et Preising 1	3	4	7
Artemisietea vulgaris Lohmeyer et al. ex von Rochow 1951	2	4	12
Polygono arenastri-Poëtea annuae Rivas-Martínez 1975	1	2	3
Plantagenetea majoris Tx. et Preising ex von Rochow 1951	1	2	6
Galio-Urticetea Passrge et Kopecký 1969	1	1	1
Bidentetea tripartiti Tx. et al. ex von Rochow 1951	1	1	4

When considering vegetation dynamics within the mining site and its immediate surroundings, the key factors influencing it must be taken into account: properties of substrates formed by extraction, the influx of seed diaspores, and the level of anthropogenic pressure. To model the effect of one factor on vegetation dynamics, most other factors should remain approximately constant. In our case, substrate characteristics – particularly texture and moisture – should be relatively constant. Seed input from surrounding natural ecosystems into disturbed ecotopes is also assumed to be relatively stable.

The balance of these factors determines not only the rate but also the direction of successional change. Under predominance of edaphic limitations, simplified pioneer phytocoenoses form, whereas under stable water-nutrient conditions, mechanisms of increasing community complexity are triggered. Thus, technogenic substrates act as a filter selectively favoring species according to their ecological tolerance.

Substrate texture and the presence of organic macromolecules (primarily humic acids) are important for autogenic succession. If the substrate consists of coarse elements and is well drained, only pioneer plants preferring extreme conditions and reduced competition will persist. Transition to higher stages of progressive autogenic succession requires constant supply of moisture and nutrients, which is ensured by the formation of capillary systems, mechanisms of solution fixation on organic polymers, or continual external inputs. For our model, substrates corresponding to sands dominated by particles 0.5–3 mm (coarse and very coarse sands) were selected. For comparison, plots outside the extraction zone with a full spectrum of multi-year moisture regimes were used, as well as quarry sites, including sandy substrate in fissures between crystalline blocks on quarry slopes.

Three groups of plant communities occur in these ecotopes. The first comprises extremophile communities – immature assemblages of mosses, lichens, and cyanobacteria with low autotroph cover. This group also includes sparse ruderal vegetation of the classes Stellarietea mediae, Artemisietea vulgaris, Polygono arenastri–Poëtea annuae, Plantagenetea majoris, Galio–Urticetea, and Bidentetea tripartiti. Within the quarry, community identification is often impossible due to the small number of species on tiny local patches. These are single individuals or small groups of Agrostis capillaris, A. vinealis, Alyssum desertorum, Ambrosia artemisiifolia, etc. (species list preserved as in the original). These species belong to eight families, with Asteraceae being the most represented (8 species), followed by Poaceae (4 species), Polygonaceae, Brassicaceae, and Fabaceae (3 species each), and Caryophyllaceae, Scrophulariaceae, and Boraginaceae (1 species each). Some of these species are diagnostic for ruderal communities. According to the pattern described by Ya.P. Didukh and P.H. Pliuta regarding the representation of families at different autogenic succession stages, such plots correspond to early stages. The synphytoindication analysis shows the natural dynamics index ranges from 1.1 to 3.7 points, while the anthropogenic transformation index ranges from 7.5 to 11.89 points. This indicates pioneer and ruderal habitat types. The formation of such communities reflects initial stages of biological colonization of technogenic substrates, where stress-tolerant species and short-lived exploiters play the leading role. Their functioning ensures primary accumulation of organic matter, stabilization of the substrate surface, and the creation of prerequisites for further vegetation development. It should be noted that in poorly developed, species-poor communities, the error of synphytoindication-based dynamic assessment exceeds 10 %. Despite their low coenotic development, these communities play a key role in initiating primary soil-forming processes: mosses, lichens, and cyanobacteria help fix silt particles, accumulate organic residues, and gradually form a thin humus-enriched horizon.

A dependence is observed between slope angle and vegetation cover. Slopes steeper than 75° are almost devoid of higher vascular plants. At slope angles of 10–30°, cover exceeds 2–3 points on the Braun–Blanquet scale, allowing identification of certain communities. On flat surfaces or slopes < 10°, cover exceeds 50 % (4–5 points). This may be explained by differences in the duration of moisture retention during precipitation events. On steep slopes, water rapidly runs off to the quarry bottom with limited contact time, so the substrate does not become saturated. Depressions at the quarry bottom become waterlogged. Here, not only the association Poto compressae–Tussilaginetum farfarae R. Tx. 1931 (Artemisietea vulgaris) occurs, but also natural meadow communities of the class Molinio–Arrhenatheretea.

The identified relationship between slope morphometry and vegetation cover highlights the decisive role of orographic factors in the spatial organization of phytocoenoses. Relief acts as a key regulator of the water regime, which in turn mediates nutrient availability and substrate stability.

Outside the quarry under similar conditions, a somewhat different pattern is observed. The sparsest plots have 3–4 points of cover, and communities are readily identifiable. These include the association Potentillo–Artemisietum absinthii Faliński 1965 (Artemisietea vulgaris) and associations Thymo pulegioidis–Sedetum sexangularis Didukh et Kontar 1998, Sedo acri–Dianthetum hypanici Solomakha, et al. 2006, Sempervivo ruthenici–Sedetum ruprechtii Didukh et Kontar 1998, and Vincetoxici hirundinariae–Rumicetum acetosellae Didukh et Kontar 1998 (Sedo-Scleranthetea). The remaining territory is occupied by mesoxerophytic meadows and dry forest edges. Differences in cover at the pioneer–ruderal and grass stages of progressive autogenic succession can be explained by a marked difference in anthropogenic pressure. Outside the quarry, anthropogenic transformation for such community types does not exceed 8 points, whereas inside the quarry it ranges from 7.5 to 11.89 points. Differences in vegetation structure are also driven by greater intensity of mechanical surface disturbance and higher recreational load within the quarry. This confirms that technogenic pressure constrains the development of dense grass cover while not fully blocking autogenic succession. As a result, a specific mosaic is formed that combines features of both degradation and recovery processes.

At later stages of progressive autogenic succession, however, the development of woody and shrub communities within the quarry does not lag behind that observed outside it under similar conditions. The quarry shows intensive formation of secondary forests of the associations Populetum nigro-albae Slavnić 1952 (Salicetea purpurea), Chelidonio-Robinietum Jurco 1963, and Sambuco nigrae-Robinietum Scepka 1982 (Robinietea). The natural dynamics index for such communities reaches 10.5 points. Woody vegetation spreads relatively evenly across suitable substrates throughout the quarry. Populus nigra and Populus alba dominate; in the north, dense thickets of Robinia pseudoacacia occur. On steep slopes near the rim, in fissures between granite blocks, Betula pendula, Pinus sylvestris, and Salix caprea are found. Outside the quarry, these substrates support sparse thickets of single individuals or typical forest-edge expansion cones; the natural dynamics index outside forest edges is approximately 7.5 points.

Active formation of secondary forests within the quarry indicates the presence of compensatory ecological mechanisms that partially offset the negative effects of technogenic disturbance. These mechanisms include increased substrate moisture, accumulation of biogenic elements, and reduced interspecific competition at early successional stages.

It can be assumed that within the quarry there are factors that create more favorable conditions for forest vegetation recovery on disturbed coarse-sand substrates. This primarily concerns differences in moisture circulation and selected biogenic elements. In the quarry, the sandy substrate thickness does not exceed 1 m and is usually only a few centimeters to tens of centimeters. Beneath it lies an impermeable weathering crust of crystalline rocks or the crystalline bedrock itself, which leads to water accumulation and increased substrate moisture. This explains the distribution of communities dominated by Tussilago farfara, whose optimum long-term moisture regime is 12 points on the Didukh-Pluta scale. Outside the quarry, the substrate overlies well-drained sandy deposits, and the impermeable horizon is deeper.

A second factor is the continuous subsidization of quarry ecosystems with plant-available nitrogen compounds (nitrates and ammonium salts) due to regular blasting. Explosives such as "Astrolite" are most often used; it is a mixture of ammonium nitrate and hydrazine compounds (hydrazine nitrate, hydrazine perchlorate). As a result of explosions, large amounts of ammonium nitrate and other related salts are released into the air. Most volatilized substances remain within the quarry, settle on its surfaces, and dissolve in water. Water analysis in the Shamraivske deposit area supports this hypothesis (Table 2).

The hydrochemical data allow drilling and blasting operations to be considered a specific source of biogenic subsidization of quarry ecosystems. Spatially, this effect is uneven: the highest concentrations of nitrates and ammonium compounds accumulate in the lowest relief elements and in weakly ventilated areas, where dust and aerosol explosion products settle and subsequently dissolve in water. Consequently, localized increases in substrate trophicity form within certain micro-ecotopes, which may facilitate a faster transition from pioneer-ruderal stages to herbaceous and woody-shrub communities. At the same time, excessive nitrogen accumulation may increase the risk of dominance by nitrophilous and synanthropic species, which should be accounted for when assessing long-term successional trajectories and predicting the stability of formed phytocoenoses.

Inputs of available nitrogen forms alter substrate trophic status and act as a catalyst for successional transformations of vegetation cover.

The analysis of ammonium and nitrate ions shows their highest concentration at the quarry bottom in the sump. This artificial water body is replenished from two sources: groundwater and precipitation. Groundwater enters the sump from deep aquifers (> 50 m) located between granite layers. The analysis indicates that nitrogen compound levels in these waters are low; however, upon entering the quarry they become enriched from the atmosphere, which is accompanied by the formation of cyanobacterial communities on waterlogged rock surfaces. Similarly, atmospheric precipitation in this area contains nitrates and ammonium salts in concentrations several times lower than those detected at the quarry bottom. No anthropogenic sources of plant-available nitrogen other than explosives are used within the quarry. The sump is located in the lowest, poorly ventilated part of the quarry; therefore, after explosions, concentrations of nitrates and ammonium salts are highest there. Salt residues from quarry walls are also washed into the sump after rainfall. Although sump water is continuously pumped into the settling pond, concentrations of these compounds in the settling pond are lower because it also receives water from outside the quarry. As water moves from the settling pond to the river, concentrations decrease further, since part of the nitrogen is absorbed by aquatic vegetation (classes Lemnetea and Potamogetea) and helophytic vegetation (class Phragmiti-Magnocaricetea) or bound in organic residues.

Thus, continuous subsidization of the quarry area with plant-available nitrogen promotes rapid colonization of sandy substrates by higher vascular plants and facilitates a quick transition from the grass stage of autogenic succession to the woody-shrub stage. An exception is hydrophilous nitrophilous communities of the class Bidentetea tripartiti, which in the Shamraivske quarry area are observed only along the banks of the Rostavytsia River. A likely reason is the absence of a seed diaspora for the edificator species of these communities. For example, zoochorous dispersal of Bidens tripartita is impeded by quarry structure, while anthropochorous dispersal of this species and Polygonum hydropiper is limited because the route between the nearest riverbank and the sump exceeds 1 km and passes through restricted-access territory. The low number of people who might transport seeds on clothing or footwear and the considerable distance make the appearance of Bidentetea tripartiti vegetation near the sump unlikely; however, this phenomenon requires further study.

Table 2

Content of nitrogen ions available to higher plants in different water bodies of the deposit

Date of analysis	Nitrogen ions available to higher plants	Sump water	Settling pond water	Discharge point water
26.03.2025	NH_4^+	0.33	0.31	0.19
	NO_3^-	19.8	13.0	5.35
27.05.2025	NH_4^+	3.4	0.54	1.95
	NO_3^-	24.2	10.4	5.45
30.09.2025	NH_4^+	2.83	0.47	0.19
	NO_3^-	20.6	8.3	5.4

Observations of vegetation self-restoration in quarries similar to the Shamraivske site suggest that over time they may develop higher coenotic diversity than would be expected in comparable areas outside mining. This is because extraction creates sites with differing orographic factor values and increases substrate diversity [12]. These substrates differ in their susceptibility to endoecogenesis; therefore, within the quarry, phytocoenoses representing different links of the autogenic successional series are present [5]. Thus, after exploitation ceases, a larger number of ecotopes occupied by more diverse vegetation will remain.

Accordingly, technogenic quarry landscapes not only recover but also generate new ecotope types with increased biotic and landscape differentiation. This enhances their role as centers of secondary biodiversity in anthropogenically transformed regions.

The formed plant communities are not only more diverse, but also have greater potential for providing ecosystem services [13]. Secondary and climax forests, deep-water aquatic ecosystems, rock-dwelling communities, and wasteland assemblages form relatively quickly [25]. Abandoned quarries influence regional species and landscape diversity and affect microclimate and water regime [4]. In the long term, such territories may function as refugia for certain groups of flora and fauna, increasing the ecological resilience of regional landscapes.

However, substrates formed during quarry operation are often poorly colonized by phanerophytes due to insufficiency of mineral nutrients [11] and the lack of systems that fix their solutions in the form of high-molecular organic compounds (humus). Blasting operations increase the concentration of some essential substances, allowing plants to grow successfully. Yet after quarry operations cease, this subsidy will stop, potentially slowing progressive autogenic succession. Accumulation of dead plant residues during long-term quarry use partly alleviates this problem, but organic matter is difficult to retain on quarry walls. A source of organic matter may be plants with symbiotic relationships with nitrogen-fixing bacteria [26]. In the Shamraivske quarry, Medicago lupulina, Trifolium arvense, Vicia cracca, and Robinia pseudoacacia are already observed. The first three species associate with relatively small amounts of nitrogen-fixing bacteria but are well adapted to such conditions. Robinia pseudoacacia is an invasive transformer species whose spread will adversely affect biodiversity. Therefore, controlled self-restoration is required, which would modify the seed diaspora by enriching it with beneficial species such as Melilotus albus, Melilotus officinalis, Medicago sativa, Trifolium repens, Onobrychis arenaria, Lupinus polyphyllus, Lotus corniculatus, and others.

Since a large portion of the quarry has disturbed vegetation cover and strong anthropogenic influence, there is a high risk of synanthropic organisms, including invasive transformer species, penetrating the area. In the Shamraivske deposit, invasive species such as Acer negundo, Ambrosia artemisiifolia, Robinia pseudoacacia, and Solidago canadensis have already been recorded, along with many synanthropic species. These species may hinder recovery of natural vegetation and lead to a "catastrophic climax". In technogenic landscapes, invasive species often exhibit increased competitiveness due to broad ecological amplitude, rapid growth, and efficient dispersal mechanisms. As a result, they can form monodominant communities that block natural successional processes and reduce floristic diversity. This necessitates continuous monitoring of vegetation recovery until stable natural communities form. Effective monitoring should integrate geobotanical surveys, remote sensing observation methods, and analysis of invasive species population dynamics, enabling timely detection of critical phases and implementation of biotechnical or phytomeliorative regulation measures. If needed, invasive species should be removed. In parallel, it is advisable to implement biological reclamation using competitive native species capable of occupying free ecological niches and preventing repeat invasion of transformer species.

Vegetation restoration models in mining sites such as the Shamraivske granite deposit correspond to those observed in areas affected by intense shelling or bombardment. The similarity of successional scenarios is driven by common key ecological factors: destruction of soil cover, formation of technogenic microrelief, changes in hydrological regime, and accumulation of explosive reaction products in substrates. The method of controlled self-restoration of natural vegetation can be applied both at mineral extraction sites and in territories affected by intensive military actions. Practical implementation of this approach opens opportunities for developing scientifically grounded strategies for ecological rehabilitation of disturbed landscapes, including optimizing the composition of phytomeliorants, forecasting recovery rates, and assessing ecosystem service potential.

The obtained results expand our understanding of vegetation self-restoration mechanisms under conditions of intensive explosive disturbance and provide a scientific basis for managing restoration processes in both mining-industrial and war-transformed landscapes.

Conclusions. Plant communities in the study area are typical of the northern Right-Bank Forest-Steppe. They formed under anthropogenic factors of varying intensity and type, as well as through vegetation self-restoration processes in disturbed habitats. They belong to 20 classes, 31 orders, 48 alliances, and 97 associations according to the Braun–Blanquet classification. The obtained phytocoenotic diversity indicators demonstrate a high degree of structural and functional differentiation of vegetation cover in the technogenically transformed territory. The combination of communities at different successional stages confirms the mosaic nature of recovery and the presence of parallel autogenic successional series.

Communities of higher vascular plants occupy only loose substrates. In fissures between blocks of crystalline rock, mostly single plants or small groups of a few individuals occur. In such fissures, plants are also tied to loose substrate between monolithic fragments of crystalline rock. This indicates the decisive role of the edaphic factor in shaping the spatial structure of quarry vegetation. Even small amounts of fine material create microhabitats suitable for the establishment of pioneer species and further development of phytocoenoses.

Vegetation cover is directly related to slope angle: on slopes steeper than 75°, higher plants are almost absent. At moderate slopes (10°–30°), cover reaches 2–3 points on the Braun–Blanquet scale, which allows identification of formed phytocoenoses. On level sites (slope up to 10°), vegetation becomes densest, exceeding 50 % cover (4–5 points).

Continuous subsidization of the quarry area with nitrogen available to higher vascular plants, formed during blasting operations, promotes rapid colonization of sandy substrates.

Grassland communities outside the quarry on similar substrates show higher cover values, but woody vegetation recovers more slowly. Inside the quarry, a diffuse distribution of young trees across suitable substrates is observed, whereas outside the quarry typical Forest-Steppe "expansion cones" occur at forest edges and clearings.

Further research should focus on quantitative modeling of vegetation successional trajectories in relation to blasting intensity, hydrochemical regime, and substrate granulometric composition. Promising directions include studying the role of microbiota in primary soil formation, assessing long-term biodiversity dynamics, and developing methods of controlled self-restoration using native phytomeliorants. The results can be used to optimize reclamation measures, forecast the ecological stability of quarry ecosystems, and restore territories disturbed by both technogenic and military impacts.

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Вектори автогенних сукцесій рослинності гранітного кар'єру за умов буро-вибухових робіт

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Мета. Провести комплексний аналіз впливу буро-вибухових робіт на формування, структуру й динаміку рослинного покриву кар'єрних територій на прикладі Шамраївського родовища гранітів. Це дасть змогу виявити закономірності автогенних сукцесій і процесів самовідновлення рослинності в умовах тривалого техногенного навантаження й оцінити роль вибухових робіт як специфічного екологічного чинника.

Методика. Методологічну основу дослідження складають польові геоботанічні методи, синтаксономічний аналіз і синфітоіндикаційний підхід. Геоботанічні описи виконані на пробних ділянках із подальшою обробкою даних у програмних середовищах Turboveg та JUICE із використанням кластерного аналізу (TWINSPAN). Для оцінки екологічних факторів середовища, рівня антропогенної трансформації та природної динаміки рослинності застосовані методи синфітоіндикації. Додатково проведено гідрохімічний аналіз водних об'єктів кар'єру.

Результати. Встановлено, що буро-вибухові роботи істотно впливають на умови формування рослинного покриву, визначаючи видовий склад, структуру й сукцесійні напрямі фітоценозів. Виявлено формування похідних рослинних угруповань, адаптованих до техногенних субстратів і підвищеного надходження біогенних елементів. Показано, що поєднання фізичного порушення середовища із хімічними й гідрологічними змінами може сприяти прискоренню окремих етапів автогенних сукцесій.

Наукова новизна. Уперше обґрунтована можливість використання діючих гранітних кар'єрів із регулярним буро-вибуховим навантаженням як модельних об'єктів для вивчення динаміки рослинності за умов інтенсивних вибухових порушень. Розширені уявлення щодо ролі вибухових робіт у формуванні сукцесійних траєкторій кар'єрних екосистем.

Практична значимість. Отримані результати можуть бути використані для екологічної оцінки кар'єрних територій, прогнозування процесів самовідновлення рослинності, обґрунтування заходів рекультивації та управління порушеними ландшафтами, а також для екстраполяції на інші території, що зазнали інтенсивних вибухових впливів, зокрема техногенного й воєнного походження.

Ключові слова: *буро-вибухові роботи, кар'єр, рослинний покрив, самовідновлення, техногенні ландшафти, автогенна сукцесія, антропогенна трансформація, синфітоіндикаційні моделі*