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Distinctive features of phytocenotic successions in mining-industrial landscapes

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Abstract. This study investigates ecological succession within quarry-stockpile complexes across the mining landscapes. Post-extraction use of quarries is often limited due to high restoration costs, technical challenges, and perceived impracticality. However, such sites can become valuable ecological assets, showcasing region-specific zonal flora. Focusing on primary succession, the research highlight shows edaphic conditions of disturbed substrates influence vegetation dynamics and broader landscape transformation. Conducted from 2019 to 2022, the study employed an integrated methodological approach, including route field surveys, aerial photography, observation, comparison, experimentation, statistical analysis, synthesis, and logical modeling to assess the plant community development. Field studies were conducted during the growing season from March to October. We determined the features of the plant cover and dominant plants in the structure of the sand quarry – stockpile complex and developed schemes of succession stages. Zoning based on the normalized difference vegetation index (NDVI) revealed a moderate expansion of highly productive phytocenoses (from 25.5% in 2019 to 27.2% in 2022) alongside a decline in the overall productive vegetation cover from 89.1% to 74.7%. Concurrently, open substrate and sparse vegetation areas expanded from 11.3% to 25.2%. The average similarity coefficient of species composition between study sites increased over time, indicating structural shifts in the plant communities. Notably, the coefficient rose from 0.54 to 0.63 on the hilly loamy-sandy surfaces, and from 0.55 to 0.81 on the rugose overburden ledges. Disturbances caused by the extraction of minerals contributed to the formation of man-made accumulative relief with a predominance of segetal-ruderal species. The findings suggest that, in the absence of active renaturalization, vegetation succession and species differentiation are largely governed by anthropogenic factors and localized ecotopic conditions. This emphasizes the ecological potential of post-mining landscapes and the importance of monitoring for informed conservation and restoration strategies.

Keywords: primary succession; normalized difference vegetation index; postmining landscapes; restoration strategies.

Introduction

A modern integrated concept of sustainable development is the creation of a comprehensive environmental protection system – an ecological network. One of the ways to optimize the ecological network is searching for promising territories and including them in structural elements that will ensure its spatial integrity and representativeness. Potential territories for inclusion in the structure of the ecological network are territories that require additional measures for renaturalization and reclamation – restoration territories, that, as part of the ecological network, will help ensure ecological balance and serve as centers of biodiversity. Such territories can be quarry and stockpile complexes for the extraction of minerals. Restoration of disturbed areas should be carried out according to landscape-ecological principles that will take into account natural factors and contribute to the formation of highly productive phytocenoses, and help cease negative impacts (Demiianyuk et al., 2025).

The emergence and transformation of phytocenoses within quarry-stockpile complexes, previously devoid of vegetation, can also occur naturally, without human intervention. The ability to change is one of the important properties of phytocenoses, as they are open systems that are influenced by external factors. Irreversible changes occurring during the replacement of some phytocenoses by others are called successions (Hryhora & Solomakha, 2000). Stages of spontaneous succession in quarries have been documented: Spontaneously formed phytocenoses were compared within individual areas in the quarries (including those of different ages and at different stages of succession); and also formed quarry phytocenoses were compared with areas of natural vegetation bordering the quarries and with reclaimed areas (Henyk & Zayachuk, 2015; Chehorka et al., 2020; Khomiak et al., 2023). The formation of the natural vegetation cover (comprising various ecological groups) on devastated substrates clearly indicate the adaptation of plants that overcome the limiting factors of the man-made environment, formed under the influence of mining activities. Moreover, studying such vegetation can aid in designing optimal recovery strategies within local conditions of disturbed areas (Mudrak & Mahdiichuk, 2022).

Spontaneous successions can make a valuable contribution to the protection of environmental components, eliminating the need for expensive reclamation methods, and the newly formed terrain can act as a secondary or replacement habitat for species (Salgueiro et al., 2020).

Further research has explored factors influencing species diversity restoration and spread mining areas (Fernández Montoni et al., 2014; Bonchkovskyi & Bezsmertna, 2020; Oliferchuk et al., 2023). Succession patterns within gypsum quarries, the spontaneous formation of forests in former coal mining areas highlight shaped landscape features and their impact on biodiversity and ecological resilience. Studies have examined phytomass changes during the initial stages of succession in sand mining areas, shedding light on their impact on substrate morphology across different ages of post-mining sand sites, providing valuable insights into ecosystem recovery trajectories. Biodiversity assessments of plant communities and soil factors in industrialized post-mining landscapes have also been conducted to better understand the habitat conditions, in particular relationships between vegetation spread rates and slope inclination angles, contributing to our understanding of landscape dynamics in post-mining areas (Lihăt et al., 2023; Mota et al., 2023).

Conditions in quarry-stockpile complexes may not be appropriate for the formation of stable phytocenoses, which requires the implementation of additional measures for reclamation and renaturalization, focused on promoting the natural restoration of degraded areas. For this purpose, various methods are used, for example: technologies for improving soil functions, based on the mechanism of regulation of "plant – microorganism – soil" interaction (Xu et al., 2023); increasing the fertility of semiarid bare soil in the quarry and enhancing the growth and survival of native plant species through the addition of organic matter; restoration of mines using different types of waste, thus ensuring the improvement of water-physical properties and elemental composition, as well as reducing the phytotoxicity of disturbed substrates (Ortega et al., 2020; Mudrak et al., 2023). The methods can differ in cost and effectiveness, and therefore various options are evaluated economically (Lorite et al., 2021).

There are well-known ways of integrating mining and industrial landscapes into the structure of cities according to the basic principles of restoration. Abandoned quarry-stockpile complexes without debris can be used as reserve areas in the structure of the ecological network, for scientific purposes or as attractive objects for geological and local-history tourism. Well-known tourist attractions in Europe include the royal salt mines of Wieliczka and Bochnia, amphitheatres (Poland), coal mines of Wallonia (Belgium), mines of Rammelsberg, coal mine Zolferain, and the Lusatian Lake District (Germany), the mining town of Rørus (Norway), coal basin in the Nord-Pas-de-Calais region (France), and the limestone quarries Butchart Gardens (Canada). Opportunities to create new tourism and recreation areas are being considered, including post-industrial sites in Luzerne and Lackawanna counties, Northeastern Pennsylvania, USA and Zabrze, Upper Silesia, Poland, and in the East-Zhushan Quarry in Xuzhou (Jia et al., 2022; Kuzior et al., 2022; Mudrak et al., 2022).

The objective of our work was to study the nature of successional changes in the ecological conditions of a quarry-stockpile complex. The hypothesis of the study was based on the idea that uneven conditions of quarry and stockpile complexes contribute to the spread of a wide range of plants. It was expected, that in the same type of sand quarry areas located within separate designated zones, phytocenoses have been formed according to similar scenarios, causing high coefficients of floristic similarity among areas within the same zone. The analysis of the course of succession stages in the local conditions of quarry and stockpile complexes is an important and necessary stage for forecasting changes in the state of the territory and planning supporting measures.

Materials and methods

Methodologies. The study of the species composition and vegetation structure of the mining and industrial landscapes included field studies during the growing season from March to October between 2019 and 2022. The period of active growing season was observed from late May to early August.

Landscape maps were created for this area as part of a space-time analysis (Mudrak & Mahdiichuk, 2022), on which separate structural units of the quarry were identified: hilly-loamy sand surfaces; rugose ledges of overburden materials; sandy slopes in the eastern quarry sector; micro-relief sand-loam surface; sandy-loam quarry-stockpile slopes; sites within shaft-shaped embankments; steep slopes; and inner slopes of sandy and loamy areas. Within each of the 8 identified units, 3 research plots of 10 × 10 meters were established.

This approach provides a broader coverage of the study, statistical reliability of the collected data, and the ability to determine whether the rates of successional transformation differ within homogeneous quarry sites. To characterize the aboveground vegetation cover, we evaluated the species composition and floristic richness, projective cover, dominant species, and the nature of anthropogenic changes of the phytocenoses. Indicators of the systematic structure were the ratio between different groups of vascular plants, expressed in % of the total number of species, families and, genera; distribution of species among different taxa; quantitative composition of leading families; and the ratio of the number of species in different families (Hryhora et al., 2000).

Identification of species was carried out in laboratory conditions based on collected herbarium specimens, the names are given according to the International Plant Name Index and the systems of S. L. Mosyakin and M. M. Fedoronchuk (1999). Anthropogenic changes in the phytocenoses within the research sites of the quarry were determined according to the distribution of ruderal species or species of transitional communities (meadow-weed, forest-weed, steppe-weed plants) (Tarasov, 2012). The description of the vegetation was carried out according to the principle of the sequence of stages of the development of phytocenoses (Hryhora, 2005).

To distinguish the dominant species, the Brown-Blanquet (1928) method was used, the projective cover was assessed according to the scale that contains the following positions: r – the species is extremely rare, the cover is insignificant; + – the species is rare and has a small projective cover; 1 – there are many individuals of the species, but the cover is small, or the individuals are rare, but the cover is large; 2 – the number of individuals is high, the projective cover reaches 5–25%; 3 – the number of individuals of any species, projective cover 25–50%; 4 – number of individuals of any species, projective cover 50–75%; 5 – the number of individuals of any species, the projective cover is more than 75% successions (Hryhora et al., 2000; Hryhora, 2005).

After obtaining the descriptions of phytocenoses in the defined areas, we compared them using the Jaccard coefficient (Popovych et al, 2024), which is calculated according to the formula:

$$K = \frac{A}{B + C - A} \quad (1)$$

A – the number of species common to this pair of descriptions, B and C – the numbers of species separately in the first and second geobotanical descriptions (phytocenoses).

The similarity coefficient ranges from 0 to 1. As the coefficient approaches 1, the similarity between two phytocenoses increases; conversely, as it approaches 0, the dissimilarity increases. Having calculated the Jaccard coefficients for the sites, it is possible to calculate the average value for the entire phytocenosis as an indicator of the homogeneity of its floristic composition. Based on the identified species and the dynamics of the appearance of plant communities, a successional series was constructed.

The terrain in the conditions of the quarry-stockpile complex was investigated using aerial photography and analysis of data from artificial Earth satellites. Using satellite data, changes in the NDVI indicator were tracked – a normalized vegetation index, which is a common tool for quantitatively assessing vegetation. The higher the density of soil covered with photosynthetically active structures, the more the reflection of waves in the bright red part of the spectrum decreases, while reflection in the dark red part increases. It is possible to estimate the potential field across large areas in advance and establish changes in land use and natural vegetation. We analyzed the features of the formation and distribution of different types of vegetation within the quarry and stockpile complex during the period of active vegetation. Systematization and analysis of the NDVI data was carried out on the basis of the EOS Crop Monitoring system.

Characteristics of Podillia. The analysis revealed a negative trend toward increase in the influence of anthropogenic factors on the natural objects of the environment – impacts of military actions, the increase in the area of unauthorized landfills, plowing, the reduction of land productivity due to their unprofitable use, changes in the purpose of land use, the mining and extraction of minerals by the open method. The latter, without meliorative transformations, indicate the urgent need to forecast possible threats to the phytocenotic diversity.

Podillia is one of the most promising and unique regions of Ukraine regarding the preservation of biotic and landscape diversity and the restoration of devastated lands. This is a historical-geographical region with an area of 60.9 thousand km^2 (10.1% of the territory of Ukraine), which, according to the administrative-territorial division, includes Ternopil (Western Podillia), Khmelnytskyi (Central Podillia), and Vinnytsia (Eastern Podillia) regions (Table 1).

Table 1
The main indicators of the regions that are part of Podillia

The name of the administrative-territorial unit	The area of the region, km^2	Number of districts, pieces	Number of territorial communities, pieces	Number of settlements, pieces	Number of population, persons
Ternopilska (Western Podillia)	13823	3	55	1058	1036590
Khmelnytskyi (Central Podillia)	20645	3	60	1451	1254702
Vinnytsia (Eastern Podillia)	26513	6	63	1503	1545416

Podillia, as a region, is situated within the Right-Bank Forest Steppe, in the southwestern part of the East-European Platform, within the Ukrainian Crystalline Massif and the Volyn-Podillia Plate. Regional features of climatic conditions change due to the significant length of the region from west to east. In addition, a noticeable increase in continentality of the climate is observed from north to south. According to the thermal and humidification regime, the climate is temperate continental, with mild winters with average January temperatures of –4 °C to –6 °C and warm, humid summers with average July temperatures of +18 °C to +20 °C. The average annual air temperature ranges 6.6 °C to 7.3 °C. Peculiarities of the geological and geomorphological structure and regionnal differences in climatic conditions determine the water balance of the territory and the conditions for the formation of the surface and groundwater regime, and also contribute to intensive water exchange in the region and the development of a relatively dense hydrographic network.

The relief of the region is very pronounced and includes a large number of deep river valleys, gullies, ravines, various hills, the steep slopes of which are eroded by water. The relief of the Right-Bank Forest Steppe is especially dissected. A characteristic feature of the region is the presence of steppe and forest areas. The average extent of plowing in the zone is 70%. A significant problem in Podillia is the degraded lands within the quarry excavations formed during extensive open-pit mining of minerals, which are characterized by major disturbances to the cover structure: during excavation, resource-rich materials are moved and exposed, while the fertile soil layer is removed; the hydrological regime is altered; and biocenotic connections are disrupted. One of the most common methods of mining in the region is open-pit sand mining in dry pits (Table 2).

Table 2
The state of sand mining in Podillia

Region	The number of deposits / of them not mined	Balance stock, thousand m^3
Eastern Podillia (Vinnytsia Region)	41/30	43,811.9
Central Podillia (Khmelnytskyi Region)	38/23	75,759.8
Western Podillia (Ternopil Region)	47/18	63,881.1

According to the obtained data, Central Podillia ranks third within Podillia (sixth in Ukraine) in terms of the number of sand mining deposits. In terms of mineral reserves, Central Podillia ranks first, with 15 quarries under development. Fertility in such areas is low, which makes such objects unsuitable for the formation of stable and rich phytocenoses. Therefore, after decommissioning of quarry and stockpile complexes, the quality of technical and biological reclamation stages remains an important and urgent issue. These measures should be aimed at restoring the territory to a favorable ecological state, suitable for profitable use and development of the biotic potential of devastated lands.

Study area. The study of the development of plant communities of mining and industrial landscapes included general scientific, empirical, and field studies within the Andriikovetskyi sand quarry and stockpile complex. This sand quarry-stockpile complex is a part of the deposits of the Sarmatian layer – the lower geological layer of the Upper Miocene of the Neogene period. The primary settlement of plants directly depends on the mechanical and physical properties of the surface layer, the exposure of the stockpiles, which determine the fixation and germination of seeds. According to the physical and mechanical properties of the sand, the substrate of the Andriikovetskyi sand quarry-stockpile complex is characterized by a dense structure and the presence of a large proportion of fine-dispersed clay, dust and silt fractions.

The Andriikovetskyi sand quarry-stockpile complex is located near the village of Andriikivtsi, Rozsosha rural territorial community, Khmelnytskyi District, Khmelnytskyi Oblast (geographical coordinates 49°18'21" N 26°48'11" E) within Central Podillia. Mining was officially stopped in 2015 (Fig. 1).

Systematic structure of the identified species in the studied region. The flora of the Andriikovetskyi sand quarry-stockpile complex included 76 species of higher vascular plants, which taxonomically belong to two divisions: Equisetophyta and Magnoliophyta. The number of species, genera, and families is an important quantitative indicator of the studied flora. The Equisetophyta division was represented by one species – *Equisetum arvense* L., its share accounting for 4.3%, and therefore the main species diversity of the quarry was observed for the Magnoliophyta division – 95.7%. As with the number of species, 92.1% belonged to the class Magnoliopsida, 6.6% to the class Liliopsida, and 1.3% to the class Equisetopsida. The leading place in the flora spectrum was occupied by family Asteraceae (16 genera), which is typical for Holarctic flora and typical for the territory of Podillia.

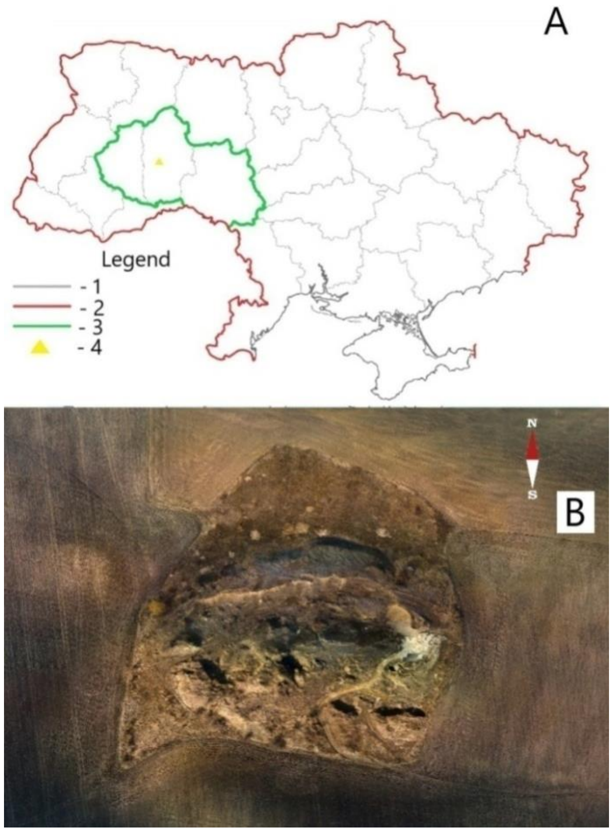

Fig. 1. Location of the Andriikovetskyi quarry and stockpile complex: *A* – the location of Podillia and the investigated quarry and stockpile complex on the map of Ukraine: *1* – boundaries of regions of Ukraine; *2* – border of Ukraine; *3* – boundaries of Podillia; *4* – location of the Andriikovetskyi quarry and stockpile complex; *B* – the general view and terrain of the quarry; developed by the authors based on their own materials

Results

Distribution of phytocenoses. In quarry-stockpileing complexes, the formation of phytocenoses, first of all, depends on edaphic conditions, the type of quarry, and the degree of disturbance of the territory. Based on the results of the previous studies, landscape maps were constructed and the main structural elements of the landscape disturbed by mining were highlighted: hilly monolithic bottom of the sand pit without vegetation; steep (up to 80°) sandy "walls" of the quarry, overgrown with various herbaceous and ruderal vegetation and isolated *Salix caprea* bushes; hilly loamy-sandy surfaces, overgrown with cereal vegetation and various herbs; rugose surface of sandy-loam stockpiles, overgrown with ruderal vegetation; slopes of sandy-loam stockpiles, overgrown with various grass-cereal, ruderal vegetation, trees and shrubs; shaft-shaped embankments, overgrown with cereal vegetation, bushes and trees (*Salix caprea*, *Prunus padus*, *Malus domestica*, *Sorbus aucuparia*); rugose ledges of overburden materials, overgrown with grass-cereal vegetation and individual trees; steep slopes of the quarry, overgrown with various herbaceous vegetation; sloping surfaces, overgrown with various grass-cereal vegetation in gray-podzolized soils; low-lying areas with sufficient moisture, overgrown with moisture-loving vegetation; single trees in the sand quarry; sandy and loamy areas within the quarry that have not been involved in mining.

During the studied period, it was found that the disturbances caused by the extraction of minerals from the Andriikovetskyi sand quarry-stockpile complex contributed to the formation of man-made accumulative relief. As a result, specific ecological conditions of the newly formed technogenic ecotopes provided a certain advantage to representatives of synanthropic species (especially with a high-invasive and dangerous potential) that are able to spontaneously infiltrate transformed semi-natural plant communities, disrupt the existing cenotic connections, isolate populations of native species, and form new phytocenoses. Altitude differentiation was observed in the distribution of vegetation cover, although the species diversity of plants remained insignificant. The quarry is located within the plakor type of terrain and has the appearance of an asymmetric pit with a depth of up to 12 m. As a result of anthropogenic changes, a fallow landscape has developed here, characterized by a pit terrain type.

The quarry has one horizon, the height of which is about 6 m. On the northern side, a dike of overburden materials, represented by sandy and clayey materials, overgrown with various grassy vegetation, is embanked. The areas adjacent to the quarry are covered with loess-like loams and gray and dark-gray podzolized soils. The sloping sections of the quarry are represented by tracts of the working ledge, composed of sandy deposits. Due to the partial appearance of vegetation, erosion processes are actively taking place here, and the materials are easily washed away by rainwater, especially from the walls of the quarry. Compared with the period after the start of research in the quarry, there was an increase in the number of spontaneous garbage stockpiles, where garbage is periodically set on fire. A recent dry fire has burned 1/3 of the quarry.

The floristic composition of the examined quarry sites had certain differences. The hilly loamy-sandy surfaces and rugose ledges of overburden materials presented a fairly diverse set of herbaceous species, including weedy and meadow species, including species common to both sites (Table 3).

Table 3
Frequency of occurrence of plants within hilly loamy-sand surfaces and rugose ledges of overburden materials of the quarry

№	Plants	Spread scale					
		2019 year			2022 year		
		1	2	3	1	2	3
	Hilly loamy-sand surfaces						
1	*Calamagrostis epigeios* L.	+	+	+	+	+	+
2	*Dactylis glomerata* L.	+	+	+	+	+	+
3	*Elytrigia repens* (L.) P. Beauv	+	1	+	+	1	+
4	*Poa pratensis* L.	+	+	+	+	+	+
5	*Ranunculus acris* L.	–	r	–	–	r	r
6	*Galium odoratum* (L) Scop	–	+	–	–	1	–
7	*Agrimonia eupatoria* L.	–	–	r	–	–	r
8	*Hypericum perforatum* L.	r	–	–	r	–	–
9	*Cichorium intybus* L.	r	r	–	+	+	+
10	*Fragaria vesca* L.	2	r	1	2	r	1
11	*Urtica dioica* L.	–	r	r	–	r	r
12	*Sorbus aucuparia* L.	–	+	–	–	+	+
	Rugose ledges of overburden materials						
13	*Ajuga reptans* L.	+	r	+	–	+	+
14	*Rumex crispus* L.	+	+	r	–	+	+
15	*Papaver rhoeas* L.	+	+	+	+	+	r
16	*Pastinaca sativa* L.	+	+	+	+	r	+
17	*Chenopodium album* L.	1	+	2	+	+	1
18	*Leonurus quinquelobatus* GilibexUsteri	+	r	r	+	r	+
19	*Echium vulgare* L.	r	–	–	+	+	+
20	*Campanula patula* L.	–	–	–	+	r	+
21	*Glechoma hederacea* L.	–	–	–	+	r	+
22	*Knautia arvensis* (L.) Coult	r	–	–	r	–	r
23	*Gallium mollugo* L.	–	–	–	+	r	r
24	*Achillea millefolium* L.	+	–	–	1	1	+
25	*Leontodon hispidus* L.	–	–	–	+	+	r
26	*Hypericum perforatum* L.	–	–	–	r	–	r
27	*Artemisia absinthium* L.	–	–	+	+	+	1
28	*Astragalus onobrychis* L.	–	–	–	+	1	1
29	*Tripleurospermum inodorum* (L.) W. D. J. Koch	r	–	r	r	+	r
30	*Stenactis annuua* L.Cass	–	r	r	+	+	1
31	*Capsella bursa-pastoris* L.	–	–	r	+	+	+
32	*Tussilago farfara* L.	2	2	2	+	1	1
33	*Rosa canina* L.	–	+	–	–	+	–
34	*Malus sylvestris* (L.) Mill.	–	–	+	–	–	+

Note. The research was conducted in 2019 and 2022 in three identical areas. Scale: r – the species was extremely rare, the cover is insignificant; + – the species was rare and had a small projective cover; 1 – there were many individuals of the species, but the cover was small, or the individuals were rare, but the cover was large; 2 – the number of individuals was high, the projective cover reached 5–25%; 3 – the number of individuals of any species, projective cover 25–50%; 4 – number of individuals of any species, projective cover 50–75%; 5 – the number of individuals of any species, the project coverage was more than 75%.

In 2019, the hilly loamy-sandy surfaces were observed to be overgrown by new plants: *Ranunculus acris* L., *Galium odoratum* (L.) Scop., *Agrimonia eupatoria* L., *Hypericum perforatum* L., *Cichorium intybus* L., *Fragaria vesca* L., and *Urtica dioica* L. The dominant plants were *Fragaria vesca* L., *Elytrigia repens* (L.) P. Beauv, and *Galium odoratum* (L.). The lowest species diversity was observed in Site 1, both in 2019 and in 2022. The plants *Ranunculus acris* L., *Hypericum perforatum* L., *Agrimonia eupatoria* L., and *Urtica dioica* L. had a limited distribution. In 2022, the distribution of segetal-ruderal species was insignificant, represented by two species – *Elytrigia repens* (L.) P. Beauv and *Urtica dioica* L. The assessed stages of succession of the studied area can be displayed as follows: In the sandy substrate monocarpic forest-steppe plants had formed; then groups of polycarpic meadow-steppe and forest-steppe grasses were established, and then forest tree species have emerged. In 2019, the vegetation of the rugose ledges of the overburden materials was characterized by uniformity, the species composition of the phytocenoses was practically identical to Site 3, where a small number of *Knautia arvensis* (L.) Coult, *Achillea millefolium* L. species in Site 1 and *Achillea millefolium* L. were observed.

In 2022, the rugose ledges of overburden materials were characterized by the appearance of a significant number of plants. The dominant plants were *Artemisia absinthium* L., *Tussilago farfara* L., *Achillea millefolium* L., *Astragalus onobrychis* L., *Chenopodium album* L., and *Stenactis annuua* L. Cass. The plants *Rosa canina* L. and *Malus sylvestris* (L.) Mill. were represented by two individuals. The population of *Tussilago farfara* L. was more sparse: The projective cover of this population decreased, and the number of individuals also decreased in Site 1, indicating the progression of the stages of succession to the next level.

Anthropogenic species were observed to make up 50% of the total species composition, including ruderal species (*Capsella bursa-pastoris* (L.) Medik, *Artemisia absinthium* L., *Chenopodium album* L., *Leonurus quinquelobatus* Gilibex Usteri, *Papaver rhoeas* L., *Stenactis annua* (L.) Cass, *Tripleurospermum inodorum* (L) Sch. Bip) and species of transitional communities (such as *Echium vulgare* L., *Glechoma hederacea* L., *Rumex crispus* L., *Tussilago farfara* L.).

The assessed stages of succession in the studied area can be displayed as follows: a *Tussilago* population formed in the clear sandy substrate; then, monocarpic ruderal grasses emerged, followed by monocarpic species with a transitional community; later, polycarpic ruderal grass species started to grow; and finally, woody forest-steppe species have overgrown the area.

The sandy slopes of the eastern part and steep slopes of the quarry were characterized by communities with more pronounced ruderal components (Table 4). *Tussilago farfara* L. is an indicator of syngenetic succession: This species had the largest projective cover in the sites within the sandy slopes of the eastern part. In some parts of the sandy slope's sites, vegetation cover was almost absent. In the places where the stages of the primary succession began, the protective cover included many exposed areas, and contained rare species with small projective cover and also extremely rare species.

In 2022, in addition to the characteristic pioneer type of plants, the area with practically no cover was inhabited by monocarpic species, such as *Tripleurospermum inodorum* L. W. D. J. Koch, *Artemisia vulgaris* L., *Atriplex sagittata* Borkh, *Artemisia absinthium* L., *Erysimum cheiranthoides* L., *Medicago lupulina* L., *Melilotus albus* Medik, and *Vicia sativa* L. There were also polycarpic herbs: *Medicago sativa* L., *Trifolium pratense* L., *Vicia cracca* L., and *Trifolium repens* L. Due to the spread of monocarpic and polycarpic type of plants in this area, the total area with no plant cover within the quarry decreased.

The dominant plants were *Tussilago farfara* L., *Trifolium pratense* L., *Vicia cracca* L., *Trifolium repens* L., *Medicago sativa* L., and *M. lupulina* L. The plant *Populus nigra* L. was represented by 3 individuals with minor phenotypic differences.

Anthropogenic species occupied 40% of the total number of species in the studied areas. They included ruderals (*Artemisia absinthium* L., *Erysimum cheiranthoides* L., *Tripleurospermum inodorum* (L) Sch. Bip) and species of transitional communities (*Tussilago farfara* L., *Melilotus albus* Medik, *Artemisia vulgaris* L., *Atriplex sagittata* Borkh). The spread of *Solidago canadensis* L. in areas with the primary stage of succession may pose a threat to the further spread of zonal plants.

The assessed course of succession stages in the studied area can be displayed as follows: In the open sandy substrate left after mining, a population of *Tussilago* has formed, and three years later, the area became occupied by monocarpic ruderal grasses and some polycarpic meadow grasses (with introduction of cultivated species).

The steep slopes of the quarry were overgrown with various herbaceous vegetation. The studied areas were not characterized by a great variety of species. Species with extremely rare projective cover and rare species with small projective cover were localized within Site 1 and Site 2. In 2022, various herbaceous vegetation was represented by *Tanacetum vulgare* L., *Taraxacum officinale* F. H. Wigg, and *Pimpinella saxifraga* L. The basis of the projective cover in all the experimental areas was *Tussilago farfara* L. Within one site, an individual of *Tanacetum vulgare* L. was encountered.

Table 4
Frequency of occurrence of plants
within the sandy slopes and steep slopes of the quarry

№	Plants	Spread scale					
		2019 year			2022 year		
		1	2	3	1	2	3
	Sandy slopes of the eastern part						
1	*Tussilago farfara* L.	3	2	1	2	2	1
2	*Tripleurospermum inodorum* (L.) W. D. J. Koch	r	–	r	r	r	–
3	*Artemisia vulgaris* L.	+	+	–	1	+	–
4	*Atriplex sagittata* Borkh	–	–	r	–	r	+
5	*Artemisia absinthium* L.	–	r	r	–	+	+
6	*Erysimum cheiranthoides* L.	r	–	–	r	+	1
7	*Medicago lupulina*L.	+	r	+	+	+	2
8	*Melilotus albus* Medik	r	+	+	–	r	r
9	*Vicia sativa* L.	r	r	r	r	r	+
10	*Medicago sativa* L.	–	–	–	r	1	1
11	*Trifolium pratense* L.	–	+	+	+	1	2
12	*Vicia cracca* L.	–	–	–	+	1	1
13	*Trifolium repens* L.	–	–	+	+	1	2
14	*Populus nigra* L.	r	–	–	r	–	r
15	*Solidago canadensis* L.	r	–	–	r	–	–
	Steep slopes						
16	*Tanacetum vulgare* L.	r	–	–	r	–	–
17	*Taraxacum officinale* F.H.Wigg	–	+	–	–	+	–
18	*Pimpinella saxifrage* L.	–	+	–	–	+	+
19	*Myosotis micrantha* PallexLehm	–	+	–	–	+	+
20	*Silybum marianum* (L.) P.Gaertn	+	–	–	+	+	–
21	*Astragalus onobrychis* L.	r	–	–	+	+	–
22	*Tussilago farfara* L.	+	+	1	r	+	2
23	*Solidago canadensis* L.	–	r	–	–	r	–

Note. The research was conducted in 2019 and 2022 in three identical areas: scale: r – the species was extremely rare, the cover was insignificant; + – the species was rare and had a small projective cover; 1 – there were many individuals of the species, but the cover was small, or the individuals were rare, but the cover was large; 2 – the number of individuals was large, the projective cover reached 5–25%; 3 – the number of individuals of any species, projective cover 25–50%; 4 – number of individuals of any species, projective cover 50–75%; 5 – the number of individuals of any species, the projective cover was more than 75%.

Segetal-ruderal species were represented by a small number of ruderals – *Cirsium vulgare* (Savi) Ten, *Myosotis micrantha* Pallex Lehm and species of transitional communities – *Taraxacum officinale* F. H. Wigg, *Tussilago farfara* L., which comprised 50% of the total number of species. The assessed stages of succession in the studied area can be displayed as follows: A bryophyte population in sandy substrate evolved into groups of polycarpic meadow-steppe grasses.

The rugose surface of sandy-loam stockpiles and shaft-shaped embankments of the quarry were characterized by stable phytocenoses, represented by a broad range of true grasses, trees, and shrubs (Table 5). The rugose surface of sandy-loam stockpiles was characterized by the appearance of the plants *Rubus caesius* L., *Cosmos bipinnatus* Cav, *Arctium lappa* L. The dominant plants were *Stenactis annua* L. Cass, *Achillea millefolium* L., *Myosotis micrantha* Pallex Lehm, *Rubus caesius* L., and *Artemisia absinthium* L. In the place of an unauthorized landfill, individuals of *Cosmos bipinnatus* Cav were found.

A significant distribution of segetal-ruderal species, which made up over 66% of the floristic composition of the community, was typical for these areas. In particular, these were ruderal species (*Arctium lappa* L., *Artemisia absinthium* L., *Capsella bursa-pastoris* (L.) Medik, *Myosotis micrantha* Pallex Lehm, *Stenactis annua* (L.) Cass) and species of transitional communities (*Carduus nutans* L., *Rubus caesius* L., *Tussilago farfara* L.).

The assessed stages of succession of the studied area can be displayed as follows: In the sandy substrate, a *Tussilago* population has formed; then, monocarpic ruderal grasses emerged, followed by polycarpic-ruderal grasses and polycarpic species with a transitional communities.

The shaft-shaped embankments were overgrown with grass vegetation and forbs, bushes, and trees, in particular *Salix caprea* L., *Sorbus aucuparia* L., *Malus sylvestris* L. Mill., and *Cerasus avium* L. Moench, which were also found in depressions. In addition, characteristic species for this part of the quarry were: *Fragaria vesca* L., *Viola arvensis* Murray, *Glechoma hederacea* L., *Malva sylvestris* L., and *Scabiosa columbaria* L.

Table 5
Frequency of occurrence of plants within rugose surface
of sandy-loam stockpiles and shaft-shaped embankments of the quarry

№	Plants	Spread scale					
		2019 year			2022 year		
		1	2	3	1	2	3
	Rugose surface of sandy-loam stockpiles						
1	*Artemisia absinthium* L.	+	+	+	1	+	+
2	*Amaranthus retroflexus* L.	+	+	r	+	+	r
3	*Capsella bursa-pastoris* L.	r	+	+	–	r	r
4	*Carduus nutans* L.	–	+	+	–	r	+
5	*Stenactis annua*(L.) Cass	+	+	+	r	1	1
6	*Elytrigia repens*(L.) P. Beauv	+	+	+	+	+	+
7	*Achillea millefolium* L.	1	+	+	1	+	+
8	*Myosotis micrantha* Pallex Lehm	r	1	+	–	1	+
9	*Rubus caesius* L.	+	+	r	1	1	+
10	*Cosmos bipinnatus* Cav	–	–	–	r	–	–
11	*Arctium lappa* L.	–	–	r	–	–	r
12	*Tussilago farfara* L.	1	+	+	+	+	+
	Shaft-shaped embankments						
13	*Calamagrostis epigeios* L.	r	+	1	+	+	1
14	*Dactylis glomerata* L.	+	r	+	+	+	+
15	*Elytrigia repens*(L.) P. Beauv	r	+	+	+	1	+
16	*Poa pratensis* L.	–	r	–	1	+	+
17	*Bromus hordeaceus* L.	+	+	1	–	r	r
18	*Salix caprea* L.	+	–	–	+	–	–
19	*Sorbus aucuparia* L.	–	+	+	–	+	+
20	*Malus sylvestris*(L.) Mill.	–	+	–	–	+	–
21	*Cerasus avium* (L.) Moench)	–	–	+	–	–	+
22	*Fragaria vesca* L.	+	r	r	+	+	+
23	*Viola arvensis* Murray	r	–	r	–	–	r
24	*Glechoma hederacea* L.	–	–	+	–	+	+
25	*Malva sylvestris* L.	–	+	+	–	+	+
26	*Scabiosa columbaria* L.	r	–	–	r	r	–

Note. See Table 4.

The dominant plants were *Elytrigia repens* (L.) P. Beauv, *Calamagrostis epigeios* L., *Poa pratensis* L. In some areas, a limited distribution of *Viola arvensis* Murray, and *Scabiosa columbaria* L. was observed.

In the studied areas, a slight spread of segetally ruderal species (21%) was recorded, including the ruderal species *Bromus hordeaceus* L. and *Elytrigia repens* (L.) P. Beauv, and the species of transitional communities – *Glechoma hederacea* L.

The assessed stages of succession of the studied area can be displayed as follows: The clean sandy substrate has overgrown by monocarpic grasses, which later changed to polycarpic ruderal grasses and polycarpic forest-steppe communities, which in turn was a prerequisite for the appearance to tree-shrub forest species.

A different trend developed within the slopes of the sandy-loam quarry stockpiles and inner slopes of the sandy and loamy areas, where the vegetation included a small number of species (Table 6). The slopes of the sandy-loam stockpiles were characterized by the appearance of two individuals of *Acer plantanoides* L. in Site 2 and Site 3. During the studied period, the proportion of polycarpic grasses increased in some areas, and in general, the plant cover was characterized by a relative uniformity and minor changes in the composition and projective cover.

In 2022, the dominant plants were *Tussilago farfara* L. and *Elytrigia repens* (L.) P. Beauv. The study areas were characterized by a high level of distribution of segetally-ruderal species, which made up 83% of the total number of species (except *Acer plantanoides* L.). The assessed stages of succession in the studied area can be displayed as follows: a bryophyte population has developed in the sandy substrate; then, monocarpic ruderal grasses spread; later, groups of polycarpic meadow-steppe grasses emerged, and next step was the appearance of the tree species of plants.

A small number of species are common on the inner slopes of sandy and loamy areas not occupied by development. As in 2019, the association is localized here *Rubus caesius* – *Equisetum arvence*, which occupies the main part of the project coverage of the studied area. Inner slopes are characterized by a small distribution of type of plants *Tussilago farfara*

L., *Astragalus onobrychis* L., *Medicago lupulina* L. Type of plants *Prunus divaricata* Ledeb represented by 1 individual.

Table 6
Frequency of occurrence plants within the slopes of sandy-loam quarry stockpiles and inner slopes of sandy and loamy areas of the quarry

№	Plants	Spread scale					
		2019 year			2022 year		
		1	2	3	1	2	3
	The slopes of sandy-loam quarry stockpiles						
1	*Cirsium vulgare* SaviTen	+	+	–	–	+	+
2	*Cirsium canum* L.	–	+	r	+	+	r
3	*Tussilago farfara* L.	1	+	+	1	r	1
4	*Crepis biennis* L.	+	+	–	–	+	r
5	*Elytrigia repens* (L.) P. Beauv	+	+	+	1	r	+
6	*Acer plantanoides* L.	–	r	–	–	r	r
	Inner slopes of sandy and loamy areas						
7	*Rubus caesius* L.	3	2	3	3	2	3
8	*Equisetum arvence* L.	1	1	1	1	+	1
9	*Medicago lupulina* L.	1	1	+	1	1	+
10	*Astragalus onobrychis* L.	1	+	+	1	1	1
11	*Prunus divaricata* Ledeb	–	+	–	–	+	–
12	*Tussilago farfara* L.	+	+	1	1	1	1

Note. See Table 4.

Tussilago farfara L. forms pioneer groups on inner slopes and is an indicator of syngenetic succession, however, formations formed in areas subject to wind and water erosion, as well as frequent material slides, are unstable and do not progress to the next stage of succession. No. 1 and 3 sites identical in floristic composition, the difference in the design coverage of *Medicago lupulina* L. species.

The research areas are characterized by a significant project coverage of two species of transitional communities – *Rubus caesius* L., *Tussilago farfara* L., which is 33% of the total number of species.

The assessed succession stages of the studied area can be depicted as follows: clean sandy substrate changed to tussilago formation, where was settlement of monocarpic meadow-steppe grasses andpolycarpic forest-steppe grasses, where was an appearance of tree-shrub type of plants.

Analysis of species composition similarity coefficients. Analysis of the similarity coefficients of species composition between the studied sites includes pairwise comparisons (No. 1 with No. 2, No. 2 with No. 3, No. 1 with No. 3) – 3 comparisons per 1 defined areas (Table 7).

The similarity coefficient within the hilly loamy-sand surfaces of the quarry in the sites 2 and 3 in 2022 increased significantly due to the spread of new species in Site 3. The similarity index was average in 2019, and high in 2022.

The average value of similarity between the sites of the rugose ledges of overburden materials in 2019 was observed; in 2022, the coefficient increased by 1.3–1.6 times, indicating a high similarity of the floristic composition of the studied areas.

Table 7
Comparative analysis of species composition similarity coefficients between sites

№	Sites	Value of the coefficients per defined areas							
		No. 1 and No. 2		No. 2 and No. 3		No. 1 and No. 3		average value	
		2019	2022	2019	2022	2019	2022	2019	2022
1	Hilly loamy-sand surfaces	0.54	0.54	0.54	0.81	0.55	0.54	0.54	0.63
2	Rugose ledges of overburden materials	0.53	0.76	0.61	0.82	0.53	0.85	0.55	0.81
3	Sandy slopes in the eastern quarry sector	0.45	0.66	0.60	0.78	0.38	0.60	0.47	0.68
4	Steep slopes	0.12	0.37	0.20	0.42	0.25	0.16	0.19	0.31
5	Rugose surface of sandy-loam stockpiles	0.90	0.63	0.90	0.90	0.81	0.72	0.87	0.75
6	Shaft-shaped embankments	0.42	0.46	0.58	0.64	0.38	0.38	0.46	0.49
7	Slopes of sandy-loam quarry stockpiles	0.66	0.50	0.50	1.00	0.40	0.50	0.52	0.66
8	Inner slopes of sandy and loamy areas	0.83	0.83	0.83	0.83	1.00	1.00	0.88	0.88

Note. The Jaccard similarity coefficient ranges 0 to 1, where values approaching 1 indicate increasing similarity between the two phytocenoses, while values approaching 0 indicate increasing dissimilarity

Coefficients of commonality of species in 2019 on the sandy slopes of the eastern part of the quarry indicates a sufficient level of similarity of the phytocenoses, despite the low level of floristic richness; in 2022, the coefficient increased by 1.3–1.5 times. The average value of the coefficients for the sites in 2022 indicates a high homogeneity of the floristic composition of the studied areas.

Such values of the similarity coefficient for the species within the rugose sand-loam surfaces of the quarry in 2019 indicate a high degree of homogeneity of the floristic composition of the experimental sites; in 2022, the decrease in the coefficients of similarity between the site 1 and 2 was due to wildfires caused by burning debris and dryness, as a result of which part of the projective plant cover was destroyed. The average value of the coefficient of similarity of the sites in 2022 still indicates a high homogeneity of the floristic composition of the studied areas.

The similarity coefficient within the slopes of the sandy-loam quarry stockpiles in 2019 indicates a high level of homogeneity between the sites 1 and 2, lower indicator between the sites 2 and 3, and the lowest similarity of No. 1 and 3 sites. The coefficient of similarity between the sites 2 and 3 indicates that both areas were characterized by the same species composition with a slight difference in the projective cover of certain species (*Tussilago farfara* L., *Crepis biennis* L., *Cirsium canum* L.). The similarity coefficient was average in 2019 and higher in 2022.

There were no significant changes in the floristic composition of sites within the shaft-shaped embankments of the quarry. The sites 2 and 3 were the most similar according to the calculated coefficients in 2019, and this trend persisted in 2022.

In 2019, the coefficient of similarity within the steep slopes of the quarry was low within the sites 1 and 2. In 2022, the coefficients of similarity between Site 2 and Site 3 have doubled, and such between Site 1 and Site 2 tripled, while the comparison of Site 1 and Site 3 revealed a decrease in the similarity between these areas. The similarity coefficient was low in 2019 and below-average in 2022.

The average values of the coefficient of similarity of the sites on the inner slopes of sandy and loamy areas within the quarry in 2019 and 2022 indicated an extremely high homogeneity of the floral composition within the inner slopes of the sandy and loamy areas.

Further forecasting of ecological changes in phytocenoses is possible under the condition of constant monitoring of the influence of natural and anthropogenic factors.

NDVI changes. Forecasting of the condition and further planning of measures for the renaturalization and stabilization of ecological and edaphic conditions, as well as observation and monitoring of trends in the formation and spread of vegetation, can be carried out remotely using the Normalized Difference Vegetation Index (NDVI) during the period of active vegetation. Monitoring of the NDVI makes it possible to detect highly productive areas, identify problem areas, and determine destructive processes in a timely manner (for example, rapid growth of weeds, reduction of productive areas, etc.), which in turn speeds up the search for solutions to improve the environmental condition of quarry and waste complexes within the mining area – industrial landscapes (Fig. 2).

Retrospective analysis of the obtained monitoring studies allows monitoring the dynamics of biomass development in the studied territory over a certain period (Table 8).

The highest productivity of the plant biomass was recorded in 2020–2021, the period when new species were introduced and erosion processes decreased on one of the slope areas. In the future, landslides were repeatedly recorded there, caused by water and wind erosion, as well as unauthorized sand mining. We observed a sharp change in the NDVI indicator in 2022, which occurred because of several areas with spontaneous combustion of garbage and dryness.

Discussion

Formation of phytocenoses. Our study was short-term – 3 years, and the duration of the experiment was influenced by the type of mineral and the age of the quarry. Khomiak et al. (2023) noted that such a study should last more than 12 years. However, the stages of succession can last longer, and the formation of groups of climatic (energy) climax sometimes requires 150–250 years. Other studies on succession have analyzed longer periods: For example Luna et al. (2022) conducted research on experimental plots for a period of 6 years; Kumar & Yarrakula (2022) studied a period of 20 years; Badraghi et al. (2023) dealt with a period of 12 to 90 years; and studies by Henyk & Zayachuk (2015) and Raska et al. (2017) analyzed long-term processes of over 50–60 years.

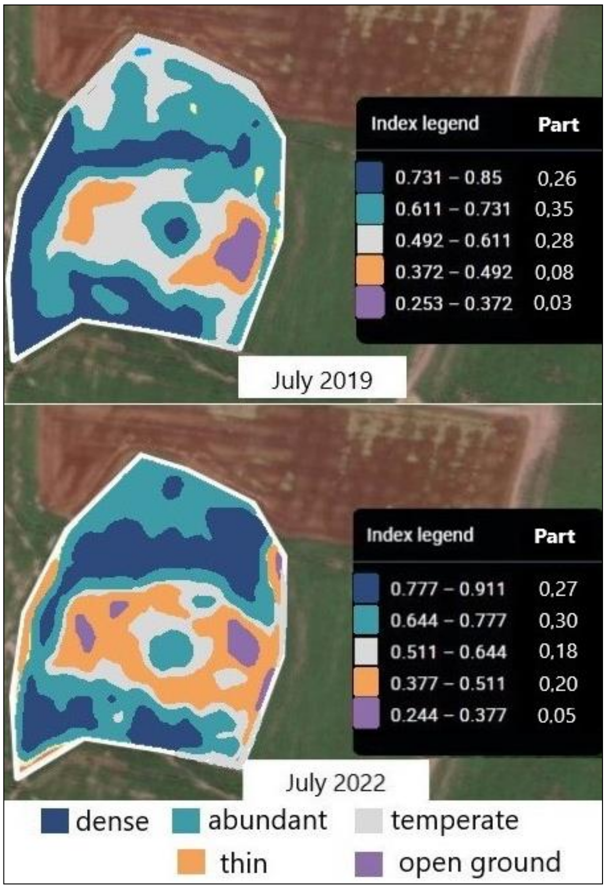

Fig. 2. NDVI zoning of the Andriykovetskyi quarry-stockpile complex: it was formed by the authors based on their own materials with Crop monitoring system

Table 8
NDVI changes for the growing season 2019–2022 (from March to October)

Period	Year			
	2019	2020	2021	2022
First half of March	0.27	0.27	0.18	0.1
Second half of March	0.27	0.27	0.28	0.24
First half of April	0.29	0.26	0.28	0.24
Second half of April	0.37	0.25	0.24	0.34
First half of May	0.52	0.40	0.42	0.48
Second half of May	0.52	0.47	0.50	0.55
First half of June	0.70	0.37	0.62	0.70
Second half of June	0.71	0.64	0.69	0.64
First half of July	0.67	0.72	0.73	0.56
Second half of July	0.60	0.70	0.67	0.55
First half of August	0.54	0.72	0.69	0.49
Second half of August	0.55	0.64	0.64	0.64
First half of September	0.38	0.56	0.57	0.58
Second half of September	0.36	0.46	0.55	0.54
First half of October	0.37	0.46	0.48	0.56
Second half of October	0.30	0.43	0.40	0.47

The analysis of the dynamics of flora changes revealed an increase in the area of phytocenotic cover within the sand quarry, but the plant cover was characterized by an uneven distribution of species. Other studies also reported uneven vegetation cover in certain areas of the mining facilities in other areas. Thus, Czortek (2023) determined the impact of landscapes near the sand-gravel quarries with a pioneer stage of succession on the phylogenetic diversity of vegetation. Kiew & Rahman (2021) noted a high level of biodiversity with the presence of several microhabitats. Olariu et al. (2024) reported that mosaicism of open terrain with areas of dense vegetation may generally be characterized by successional divergence. Kotkova et al. (2025) observed depleted vegetation cover both within the deposit and within the sanitary protection zone.

The Andriikovetskyi sand quarry was characterized by species differentiation and different stages of succession in individual parts of the quarry. A similar result was obtained during a three-year observation of a quarry: more than 70% of the identified plants were zonal species, however, in some areas the succession stages did not correspond to the late stages of succession (Atkinson et al., 2021).

The created geological and geomorphological conditions of this quarry clearly distinguish catenas, which serve as transitional zones between the territories examined in this study and the surrounding environment, and contribute to the spread of zonal biodiversity of Podillia (Lyubinska & Yuglichek, 2017; Tkach & Shavrina, 2019). Catenas have the properties of semi-natural phytocenoses where the spread of phytodiversity occurs faster. Although this quarry is isolated relative to natural (forest and aquatic) and seminatural (field shelterbelts, pastures, and hayfields) ecosystems, the zonal floristic and faunal biodiversity can spread within its boundaries.

Phytocenoses' similarity. The highest similarity coefficients were recorded at sites on the inner slopes of sandy and loamy areas. The lowest similarity coefficient was recorded within the experimental sites on rugose ledges of overburden materials, on the steep slopes and sandy slopes in the eastern quarry sector. The slopes of the eastern section were characterized by pioneer plant colonization, but the destructive processes within them continue, highlighting the need for reclamation measures to stabilize the conditions and promote the development of a stable phytocenotic cover (Mudrak et al., 2023). Stable phytocenoses, characterized by an increase in species richness, were formed mainly near stable edges (Stephan & Hubbart, 2022), and due to the high risk of erosion processes, repopulation of plants, young plants do not develop (Correia et al., 2001). With our results, this confirms the need for technical reclamation.

Other studies indicate the presence of all levels of similarity, which is similar to our results: high level of similarity coefficient were found (0.75), as well as average (0.45) and very low (0). Low similarity coefficients, measuring 0.15–0.26 and 0.18–0.30, are evidence of different stages of succession, fragmentation, and different environmental conditions (Popovych et al., 2024).

Remote sensing as a successful means of monitoring destructive areas. Methods of studying disturbed areas using satellite images and NDVI monitoring are becoming widespread among researchers: They record changes in vegetation (Kuzevic et al., 2022; Himmy et al., 2024), and help create maps. In particular, they allow for recording changes in the areas of quarries where mining continues, changes in the state of phytocenoses on barren soils, and aid in developing methods for their biological reclamation (Koptieva, 2023; Meena et al., 2024). A significant advantage of such methods is the ability to observe the research object in case of inaccessibility and at a convenient time.

Zoning based on the NDVI revealed a slight change in the index: a moderate expansion of highly productive phytocenoses—from 0.26 in 2019 to 0.27 in 2022—alongside a decline in the overall productive vegetation cover from 0.89 to 0.75. Concurrently, open substrate and sparse vegetation areas expanded from 0.11 to 0.25. Similar low levels of cover were recorded in other areas, where the ecological environment improved, but only reached an average level of cover (Wang et al., 2022). The same trend was observed in the quarry surrounded by agricultural land, in which case a significantly lower NDVI is expected (Toplicanu et al., 2025). A significant difference in the intensity and condition of vegetation over time was observed: The highest NDVI values were exhibited by deciduous forests, measuring 0.83 on average, while agricultural lands showed an average value of 0.71 and shrubs showed an average value of 0.68 (Priya et al., 2023).

With NDVI we recorded the uneven passage of succession stages at the quarry site, which lead to the formation of large ecotone areas, considered to be among the most vulnerable to incursion of invasive species (Khomiak, 2022; Malenko et al., 2024). The NDVI also revealed a significant number of ruderal plants. Ruderal species can be perceived as a biological signal that degraded land is capable of recovery, and therefore these species are studied for their ability to accumulate inorganic and organic pollutants and their potential for use in reclamation of degraded lands (Ranđelović & Jovanović, 2023). In our case, this species are a threat to the natural flora of the region.

A significant advantage of such methods is the ability to observe the research object in case of inaccessibility and it is possible to supplement the already obtained research data. However, the trend in the use of NDVI has certain shortcomings, which can affect the result of vegetation cover assessment (Huang et al., 2021).

The further role of quarries in biodiversity conservation. It is difficult to choose a direction for profitable use of quarries due to a number of factors, such as: the high cost of restoration measures; the complexity of implementing engineering and mining stages of reclamation; the inexpediency of afforestation or using quarries for growing crops. At the same time, such quarries can become valuable objects that represent the unique zonal flora of the region.

The value of the abandoned quarry in biodiversity conservation is interpreted from the point of view of landscape architecture, since the modified relief is sharply different from the natural elements of the landscape and contains a variety of natural and anthropogenic complexes in a relatively limited area. Pioneer species play an important role in creating suitable conditions for more habitat-demanding species. Therefore, a further recovery strategy should include the preservation of primary natural succession, and should be applied as an effective solution to support diverse habitats of endangered species, especially near Natura 2000 sites (Pratiwi et al., 2021; Halevy et al., 2023). Abandoned quarries can promote new ecological niches and significantly diversify rural landscapes (Germano et al., 2016).

The keys to restoring ecosystem balance in quarries are native species, which adapted to local conditions, ensuring the stability of phytocenoses, contributing to the formation of sustainable succession processes, and support of natural biodiversity (Winkler et al., 2014; Luna et al., 2022).

In the process of restoration of vegetation cover, the territory of the Andriikovetskyi quarry-stockpile complex will demonstrate a variety of meadow and meadow-steppe ecosystems within the Buzhotsko-Buzko-Vovksko-Smotrytskyi eco-corridor of the Central Podillia regional econetwork. In addition, the Andriikovetskyi quarry-stockpile complex can perform environmental protection functions as an conservation object – a reserve. The quarry can be the basis for the creation of the following types of reserves (only if there is scientific justification): ornithological (the appearance of birds such as *Corvus corax*, *Perdix perdix*, *Apus apus* was recorded; they are included in Appendix III of the Bern Convention); botanical (after taking the recommended measures to stabilize the edaphic conditions, the quarry can play the role of a biodiversity hotspot for regionally rare species of Central Podillia); general geological: (these are unique geological objects that can perform recreational and tourist functions).

Conclusions

A significant number of mineral extraction sites, including numerous sand mining operations, are located within the study region. Sand extraction leaves behind a low-productivity layer of bare substrate that is deficient in essential compounds and nutrients, particularly humus. This layer also exhibits poor water retention, low structural stability, and a disturbed composition. These conditions hinder natural regeneration, impede the establishment of stable plant communities, and contribute to landscape degradation and biodiversity loss. Establishing plantations is a cost-effective and efficient method for quarry restoration, while phytoremediation accelerates the natural recovery of degraded land. Over three years of observations, the areas that were previously resistant to plant colonization have shown improvement, with both mono- and polycarpic grasses beginning to establish themselves. Destructive processes continue on the sandy slopes in areas with ongoing unauthorized mining. Addressing these limiting edaphic factors is crucial for fostering the formation of zonal natural flora. According to our research hypothesis, all selected zones undergo succession stages according to similar scenarios, except for areas with a low similarity coefficient. The absence of renaturalization measures within the study area suggests that species differentiation is primarily driven by anthropogenic influences and the resulting ecotopic conditions. Continued monitoring, particularly through remote sensing, will help track changes in plant cover and assess the impact of human activity on the development of stable plant communities. There are significant challenges in identifying viable post-extraction uses for quarries due to high remediation costs, complex engineering and reclamation requirements, and the impracticality of converting sites to forest or agricultural land. However, they have the potential to serve as valuable conservation sites, showcasing unique zonal flora and functioning as integral elements of ecological networks for landscape restoration. In some cases, quarries preserve conditions similar to prehistoric or destroyed landscapes, allowing the survival of certain types of flora that are almost no longer found in other parts of the region. The results of this study were used to develop schemes for assessing the ecological condition of phytocenoses within quarry-stockpile complexes. These schemes can be applied to evaluate mineral extraction sites and devastated lands as existing structural elements of the regional ecological network, particularly as biodiversity cells.

References

Badraghi, A., Krucek, M., Kral, K., Reitschmiedova, E., Salek, V., Kotapisova, M., Novotna, B., & Frouz, J. (2023). Woody species succession and spontaneous forest development in post-mining sites after coal mining in the Czech Republic. Ecological Engineering, 194, 107051.

Bonchkovskyi, A., & Bezsmertna, O. (2020). Osoblyvosti roslynnoyi suktsesiyi u karieri tsehel'noho zavodu v s. Novyi Tik [Features of vegetation succession in the loess quarry of the brick factory in Novyi Tik Village (Rivne Region, Ukraine)]. Visnyk Kyivskoho Natsionalnoho Universytetu imeni Tarasa Shevchenka, Biolohiia, 80, 44–49 (in Ukrainian).

Chehorka, P. T., Maniuk, V. V., Syzhko, V. V., & Kolesnyk, V. M. (2020). Bioriznomanittia Rybalskoho karieru ta shliakhy yoho zbahachennia [Biodiversity of the Rybalskiy quarry and ways to enrich it]. Monitorynh ta Okhorona Bioriznomanittia v Ukrayini. Prykladni Aspekty Monitorynhu ta Okhorony Bioriznomanittia. Seriia: Conservation Biology in Ukraine, 16(3), 473–489 (in Ukrainian).

Correia, O., Clemente, A. S., Correia, A. I., Máguas, C., Carolino, M., Afonso, A. C., & Martins-Loução, M. A. (2001). Quarry rehabilitation: A case study. WIT Transactions on Ecology and the Environment, 46, 331–346.

Czortek, P. (2023). Landscape-driven effects on taxonomic, functional, and phylogenetic diversity of vegetation developing on sand-gravel pits of early successional stages. Ecological Informatics, 76, 102123.

Demyanyuk, O., Mudrak, O., & Mahdiichuk, A. (2025). Hirnycho-promyslovi landshafty Podillia yak potentsiyni strukturni elementy rehionalnoyi ekolohichnoyi merezhi [Mining and industrial landscapes of Podillia as potential structural elements of the regional ecological network]. Agrarna Nauka, Kyiv (in Ukrainian).

Fernández Montoni, M. V., Fernández Honaine, M., & Del Río, J. L. (2014). An assessment of spontaneous vegetation recovery in aggregate quarries in coastal sand dunes in Buenos Aires Province, Argentina. Environmental Management, 54(2), 180–193.

Germano, D., Machado, R., Godinho, S., & Santos, P. (2016). The impact of abandoned/disused marble quarries on avifauna in the anticline of Estremoz, Portugal: Does quarrying add to landscape biodiversity? Landscape Research, 41(8), 880–891.

Halevy, C., Sebrechts, T., & Sparg, S. (2023). Conservation easements – project selection criteria for quarries in Europe. Frontiers in Conservation Science, 4, 1304712.

Henyk, Y., & Zayachuk, V. (2015). Suktsesiyi roslynnosti na posttekhnohennykh terytoriyiakh Kolomyiskoho Burovuhilnoho Rodovyshcha [Successions of plantations on post-technogenic territories of Kolomyja Brown Coal Deposit]. Naukovyi Visnyk NLTU Ukrainy, 25(6), 119–124 (in Ukrainian).

Himmy, O., Nguyen, T. T., Hemmler, K. S., Loulad, S., Rhinane, H., & Buerkert, A. (2024). Leveraging machine learning and Landsat time series for high-resolution mapping of mining-induced vegetation changes in Ouagadougou, Burkina Faso. Environmental Challenges, 17, 101026.

Hryhora, I. M. (2005). Poliovyi praktykum z botaniky [Botany field workshop]. Aristei, Kyiv (in Ukrainian).

Hryhora, I. M., & Solomakha, V. A. (2000). Osnovy fitotsenolohiyi [Basics of phytocenology]. Fitosotsiotsentr, Kyiv (in Ukrainian).

Huang, S., Tang, L., Hupy, J. P., Wang, Y., & Shao, G. (2021). A commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. Journal of Forestry Research, 32, 1–6.

Jia, L., Lin, Q., Wang, X., & Zhang, S. (2022). Vegetation restoration strategies for abandoned quarry from the perspective of landscape architecture. Landscape Architecture, 29(9), 84–91.

Khomiak, I. V. (2022). Syntaksonomiya vidnovliuvanoyi roslynnosti karieriv Tsentralnoho Polissia [Syntaxonomy of restoration vegetation in quarries in Central Polissya]. Ukrainian Botanical Journal, 79(3), 142–153 (in Ukrainian).

Khomiak, I. V., Bren, A. L., Medvid, O. V., & Khomiak, A. K. (2023). Dynamika roslynnosti sukhodolu na terytoriyi karieriv yak model' postmilitarnoho vidnovlennia dykoyi pryrody [Dynamics of terrestrial vegetation on

the territory of quarries as a model of post-military restoration of wild nature]. Ukrainskyi Zhurnal Pryrodnychykh Nauk, Heohrafiia, 5, 61–69 (in Ukrainian).
Kiew, R., & Rahman, R. A. (2021). Plant diversity assessment of karst limestone, a case study of Malaysia's Batu Caves. Nature Conservation, 44, 21–49.
Koptieva, T. S. (2023). The reclamation of the surface layer of mining landscapes of Kryvyi Rih landscape technical system. Man and Environment, Issues of Neoecology, 39, 55–64.
Kotkova, T. M., Kotyuk, L. A., Yaremenko, O. V., & Stotska, S. V. (2025). Doslidzhennia stanu uhrupovan' flory za vplyvu promyslovoyi rozrobky Sokyrnytskoho Rodovyshcha tseolitiv Khustskoho Raionu Zakarpatskoyi Oblasti [Study of flora communities under the impact of industrial mining at the Sokyrnytsia Zeolite Deposit in the Khust District of the Zakarpattia Region]. Ukrainian Journal of Natural Sciences, 11, 280–293 (in Ukrainian).
Kumar, V., & Yarrakula, K. (2022). Environmental impact assessment of limestone quarry using multispectral satellite imagery. Earth Science Informatics, 15, 1905–1923.
Kuzevic, S., Bobikova, D., & Kuzevicova, Z. (2022). Land cover and vegetation coverage changes in the mining area – a case study from Slovakia. Sustainability, 14(3), 1180.
Kuzior, A., Grebski, W., Kwilinski, A., Krawczyk, D., & Grebski, M. E. (2022). Revitalization of post-industrial facilities in economic and socio-cultural perspectives – a comparative study between Poland and the USA. Sustainability, 14(17), 1101.
Lihăt, I., Ványolos, E., Henning, A. I., Hegedüs, N. M., Szekely-Varga, Z., & Kentelky, E. (2023). Injuries in the landscape: The Suseni quarry – a case study from Transylvania, Romania. Acta Universitatis Sapientiae, Agriculture and Environment, 15(1), 139–151.
Lorite, J., Ballesteros, M., García-Robles, H., & Cañadas, E. M. (2021). Economic evaluation of ecological restoration options in gypsum habitats after mining. Journal for Nature Conservation, 59, 125935.
Luna, L., Lázaro, R., Miralles, I. & Solé-Benet, A. (2022). Opportunistic vegetation in quarry soil restoration from semiarid South East Spain: Pines and spontaneous species. Land Degradation and Development, 33(17), 3617–3629.
Lyubinska, L., & Yuglichek, L. (2017). Flora Khmelnychchyny [Flora of the Khmelnytskyi Region]. Polihrafist, Khmelnytskyi (in Ukrainian).
Malenko, Y., Kobriushko, O., & Verba, D. (2024). Osoblyvosti ekomorfichnoho skladu uhrupovan' roslyn tekhnohennykh ekotopiv vidvaliv Kryvbasu [Peculiarities of ecological composition of plant communities in technogenic ecotopes of Kryvbas Dumps]. Ekolohichni Nauky, 53, 134–149 (in Ukrainian).
Meena, G. L., Sharma, G. K., Kumawat, A., Ali, S., Kumar, A., Meena, H. R., Kumar, K., Rashmi, I., Meena, R. S., & Meena, R. B. (2024). Application of remote sensing and GIS for monitoring mine spoil areas: A case study of Kota Stone Mines. In: Sharma, G. K., Rashmi, I., Ali, S., Kala, S., Kumar, A., & Madhu, M. (Eds.). Ecological impacts of stone mining. Springer, Singapore. Pp. 57–69.
Mosyakin, S. L., & Fedoronchuk, M. M. (1999). Vascular plants of Ukraine. A nomenclatural checklist. M. G. Kholodny Institute of Botany, Kiev.
Mota, J. F., Martínez-Hernández, F., Salmerón-Sánchez, E., Mendoza-Fernández, A. J., Pérez-García, F. J., & Merlo, M. E. (2023). Spontaneous primary succession and vascular plant recovery in the Iberian gypsum quarries: Insights for ecological restoration in an EU priority habitat, Plants, 12(5), 1162.
Mudrak, O. V., Demyanyuk, O. S., & Mahdiichuk, A. P. (2022). Hirnychopromyslovi landshafty Pravoberezhnoho Lisostepu yak potentsiyni strukturni elementy rehionalnoyi ekomerezhi [Mining and industrial landscapes of the Right Bank Forest Steppe as potential structural elements of the regional eco-network]. Ekolohichni Nauky, 43, 149–153 (in Ukrainian).
Mudrak, O. V., Mahdiichuk, A. P., & Mudrak, H. V. (2023). Zmina fitotoksychnosti substrativ pishchanykh karierno-vydvalnykh kompleksiv Tsentral'noho Podillia pid vplyvom potentsiyno-rodiuchykh porid [Phytotoxity change of the substrates of sand quarry and dump complexes of the Central Podillia under the influence of potentially-fertile rock]. Visnyk Natsionalnoho Universytetu Vodnoho Hospodarstva ta Pryrodokorystuvannia, Seriia: Silskohospodarski Nauky, 4, 115–126 (in Ukrainian).
Mudrak, O., & Mahdiichuk, A. (2022). Mining and industrial landscapes of Podillya as potential structural elements of the regional ecological network. Scientific Horizons, 25(4), 88–99.
Olariu, H. G., Wilcox, B. P., & Popescu, S. C. (2024). Examining changes in woody vegetation cover in a human-modified temperate savanna in Central Texas between 1996 and 2022 using remote sensing. Frontiers in Forests and Global Change, 7, 1396999.
Oliferchuk, V., Shukel, I., & Kuzyarin, O. (2023). Ekoloho-biolohichna struktura flory devastovanykh zemel sirchanykh karieriv [Ecological and biological structure of flora of devasted lands at surfur quarries]. Ahroekolohichnyi Zhurnal, 1, 65–75 (in Ukrainian).
Ortega, R., Domene, M. A., Soriano, M., Sánchez-Marañón, M., Asensio, C., & Miralles, I. (2020). Improving the fertility of degraded soils from a limestone quarry with organic and inorganic amendments to support vegetation restoration with semiarid Mediterranean plants. Soil and Tillage Research, 204, 104718.
Popovych, V., Skyba, T., Koval, V., Bosak, P., & Kopystynskyi, Y. (2024). Ecological successions of urban landfills of the Western Forest Steppe of Ukraine. Ecological Engineering and Environmental Technology, 25(7), 225–233.
Pratiwi, Narendra, B. H., Siregar, C. A., Turjaman, M., Hidayat, A., Rachmat, H. H., Mulyanto, B., Suwardi, Iskandar, Maharani, R., Rayadin, Y., Prayudyaningsih, R., Yuwati, T. W., Prematuri, R., & Susilowati, A. (2021). Managing and reforesting degraded post-mining landscape in Indonesia: A review. Land, 10(6), 658.
Priya, M. V., Kalpana, R., Pazhanivelan, S., Kumaraperumal, R., Ragunath, K. P., Vanitha, G., Nihar, A., Prajesh, P. J., & Vasumathi, V. (2023). Monitoring vegetation dynamics using multi-temporal normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) images of Tamil Nadu. Journal of Applied and Natural Science, 15(3), 1170–1177.
Randelovic, D., & Jovanovic, S. (2023). Understanding the role of ruderal plant species in restoration of degraded lands, bio-inspired land remediation. In: Pandey, V. C. (Ed.). Bio-inspired land remediation. Springer International Publishing, Cham. Pp. 31–67.
Raska, P., Riezner, J., Pokorny, R., Holec, M., & Raska, M. (2017). Relations between biotic and abiotic diversity in abandoned basalt quarry and its relevance for ecologic restoration (Radobýl Hill, Northern Czechia). Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 65(1), 151–166.
Salgueiro, P. A., Prach, K., Branquinho, C., & Mira, A. (2020). Enhancing biodiversity and ecosystem services in quarry restoration – challenges, strategies, and practice. Restoration Ecology, 28(3), 655–660.
Stephan, K., & Hubbart, J. A. (2022). Plant community, soil and microclimate attributes after 70 years of natural recovery of an abandoned limestone quarry. Land, 12(1), 117.
Tarasov, V. V. (2012). Flora of Dnipropetrovs'koyi ta Zaporiz'koyi oblastey [Flora of Dnipropetrovsk and Zaporizhia regions]. Lira, Dnipropetrovsk (in Ukrainian).
Tkach, Y. D., & Shavrina, V. I. (2019). Ekolohichna rol' spoluchnykh terytoriy u formuvanni ekomerezhi Skhidnoho Podillia [Environmental role or connecting territories in the formation or the ecological network of the Eastern Podillia]. Ahroekolohichnyi Zhurnal, 3, 20–27 (in Ukrainian).
Topliceanu, T.-S., Fanaru, G., Vizireanu, M.-G., & Telea, A. E. (2025). Assessment of renaturation in active and inactive quarries using remote sensing data. Annals Academy of Romanian Scientists Series on Biological Sciences, 14(1), 30–46.
Wang, Y., Qiao, L. F., Yao, Z. Y., Qi, A. G., & Zhang, Y. C. (2022). Analysis of the change in vegetation coverage of chalk soil wasteland during the growing season based on UAV sequence image. Applied Ecology and Environmental Research, 20(4), 3311–3322.
Winkler, N., Weymann, W., Auge, H., Klotz, S., Finkenbein, P., & Heilmeier, H. (2014). Drought resistance of native pioneer species indicates potential suitability for restoration of post-mining areas. Web Ecology, 14, 65–74.
Xu, D., Li, X., Chen, J., & Li, J. (2023). Research progress of soil and vegetation restoration technology in open-pit coal mine: A review. Agriculture, 13(2), 226.