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Restoring Soil Cover and Plant Communities with Arbuscular Mycorrhizal Fungi as an Essential Component of DSS for Environmental Safety Management in Post-Industrial Landscapes

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Abstract: Large areas become unsuitable for full-fledged life after mining activity. To improve the state of environmental safety of post-industrial landscapes and the rational use of disturbed territories, a Decision Support System (DSS) should be created. This system should also contain proposals for restoring the soil cover and plant communities that are proposed in this article. The purpose of this study is to determine the influence of arbuscular mycorrhizal fungi on the process of vegetation formation in the post-industrial landscape of a sulfur quarry. During reclamation works in human-made ecotopes, vegetation has already formed there in a certain way due to natural succession processes. We assessed the level of vegetation self-restoration and, on the basis of the obtained data, the need and direction of phytoreclamation in relation to specific ecotopes. The set of restoration of soil cover and plant communities makes it possible to solve the problem of reusing post-industrial landscapes. The positive effect of the treatment of seedlings with a spore remedy of arbuscular, mycorrhizal fungi on the studied breeds' height increase was observed. In the process of the revitalization of disturbed landscapes through the mycorrhization of planting material, there is a tendency to restore and increase phytodiversity at the floristic and coenotic levels.

Keywords: human-made ecotope; succession; ectomycorrhiza; mycotrophy; embryozems; florocenocomplexes; sulfur quarry

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1. Introduction

Ukraine is one of the world leaders in native sulfur reserves. The Lviv region is the most powerful mining region in the west of Ukraine. There are more than 620 deposits of various minerals on its territory, of which 247 are being exploited. The region produces and enriches coal, oil, gas, native sulfur, potassium salts and many other minerals. The mining and chemical industry occupies one of the leading places in the infrastructure of the country's economy. However, at the same time, the activity of mining and chemical enterprises is a determining factor of technogenesis, which significantly complicates the ecological situation in local areas with changes in landforms and hydrological and biogeochemical regimes caused by the accumulation of significant waste on the ground. As a result, there are various environmental problems, primarily related to the pollution of numerous natural components of the environment—soil, water and vegetation—thus, the deteriorating health of the local population [1–4]. One of the industrial basins that has undergone intensive exploitation is the Pre-Carpathian sulfur-bearing basin. The main objects within the sulfur-bearing basin for which mining operations were performed were State Enterprise (SE) "Rozdil Mining and Chemical Enterprise (MCE) "Sirka"" and Yavoriv State Mining and Chemical Enterprise (SMCE) "Sirka". Today, the sulfur mining industry has ceased to exist. The state balance includes seven deposits of native sulfur. The Resolution of the Cabinet of Ministers of Ukraine No442 in 1995 decided to close sulfur production. The unregulated extraction of sulfur in the open area on the site of former sulfur deposits leads to damage to the natural landscape, the accumulation of human-made waste and pollution of soil and water bodies. The activity of mining and chemical enterprises of the region has led to many negative environmental consequences, in particular: 2240.0 hectares of disturbed and contaminated lands; 3 million tons of phosphogypsum, 71.5 million m^3 of flotation tailings and 13 million tons of saturated brines were accumulated; 950 sulfur production and drainage wells; 30 million m^3 of underground cavities; 38 karst failures [5–8].

The natural and technical systems of post-industrial landscapes are not balanced. Maintaining homeostasis requires a constant supply of external energy. The cessation of energy supply causes the development of processes, as a result of which, the system approaches natural equilibrium or, in other words—post-industrial landscape self-restoration. During this period, the natural and technical system changed under the influence of post-industrial mining (after the completion of mining operations) and by self-recovery. Over time, post-industrial mining ceases, and the processes of self-recovery continue and fade as the balance is reached. Restorative processes can activate mycorrhizae.

Some artificial practices, such as coal mining, disrupt this and lead to environmental degradation. Mining subsidence induces cracks in the soil surface and damage to plant roots, leading to plant death and vegetation degradation. It is, therefore, important to devise methods for the ecological restoration of mining areas.

Vahter et al. [9,10] conducted a study in northeastern Estonia, and it was demonstrated that the co-introduction of native plants and AM (arbuscular mycorrhizal) fungi is an effective way to establish species-rich vegetation in post-industrial areas. The cointroduction of symbiotic partners resulted in higher richness, diversity and abundance of plants and AM fungi than when either partner was introduced individually. However, the plant and AM fungal communities in sown and inoculated plots were not distinct from those in uninoculated treatments; rather, they formed a subset of all taxa present on the sites but exhibited higher diversity than in uninoculated plots.

Efforts to rehabilitate vegetation in post-industrial landscapes have been ongoing since the 1940s, but restoring grassland plant communities has proven to be challenging even with traditional techniques. Compared to naturally occurring ecosystems, conventional restoration methods often result in low plant diversity. This may be due to certain practices, such as the use of fertilizers to enrich nutrient-poor soil or the introduction of species that are not well-suited to the habitat conditions. In addition, restoration efforts that solely focus on plants without considering their associated microbiomes have been identified as a factor in these failures. Mycorrhizal fungi, which are an essential part of most plant microbiomes, play a particularly important role in grasslands, with arbuscular mycorrhiza (AM) being the most prevalent type of mycorrhizal symbiosis. AM fungi supply plants with vital nutrients such as nitrogen and phosphorus, improve their resistance to biotic and abiotic stresses and receive photoassimilated carbon from the plants in return. In post-industrial landscapes, where extreme environmental conditions often prevail, AM fungi may be crucial for plant survival and vegetation restoration. Several studies suggest that introducing a diverse range of native AM fungal communities into these sites could provide numerous benefits, including accelerated vegetation establishment. However, most mine restoration experiments have focused on a limited selection of AM fungi, and there is a dearth of research on the co-development of native AM fungal communities and their host plants. Inoculation experiments have often been carried out in greenhouse conditions using only a small number of plant species, leading to conflicting reports on the success of the approach, particularly with regard to plant diversity [11–17].

During reclamation works in human-made ecotopes, we often have to face the fact that vegetation has already formed there in a certain way due to natural succession processes. It is necessary to assess the level of such self-restoration and, on the basis of the obtained data, the need and direction of phytoreclamation in relation to specific ecotopes. However, the poor nutrient substrate in the ash substrate does not allow the plants to inhabit the area quickly enough. Therefore, mycorrhiza is extremely important in soil formation and the maintenance of soil fertility, which, together with plant organisms, creates a system that has the characteristics of a whole organism [18]. Mycorrhizal plants are inhabited on the outside by epiphytic and on the inside by endophytic microorganisms. They are densely located in the rhizosphere (at a distance of 0.5 cm from the roots), in the rhizoplane (at the root), in the phyllosphere (in the air) near the terrestrial organs, phylloplane (on the surface of the latter) and in the internal tissues of plants. Thus, the influence of mycorrhiza in plant associations has created theoretical and practical interest and determines the relevance of this study.

The restoration of soil cover and plant communities is a critical component of Decision Support Systems (DSSs) for environmental safety management in post-industrial landscapes. By incorporating restoration strategies into Decision Support Systems, environmental managers can help to ensure the long-term health and safety of these landscapes for both people and the environment [6,7,18–24].

The geoinformation system of the monitoring of post-industrial landscapes should be based on the assessment of all sources of an environmental hazard: soil, the water environment, industrial waste and geophysical changes [6].

The system should contain a data bank, geoinformation maps and software. The software product combines the database system with electronic mapping; provides a search of objects on a geographic information map; reviews information about monitoring objects; analyzes data on the quality of components of the environment and hazard sources of the post-industrial landscapes; and automatically maps locations of points of selection samples, discharges, water intakes, the construction of thematic maps, etc.

The purpose of this study is to determine the influence of arbuscular mycorrhizal (AM) fungi on the process of vegetation formation in post-industrial landscapes of the sulfur quarry in question.

To test our hypotheses, we conducted a study where we examined the plant and AM fungal community composition. Our primary goal was to determine whether native AM fungal inoculation and the addition of plant seeds impacted the diversity of both plants and AM fungal communities compared to uninoculated or unseeded treatments. We hypothesized that:

Introducing native AM fungi through inoculation would result in a greater diversity of both plants and AM fungi compared to treatments without inoculation;

Adding plant seeds would also increase the diversity of plants and AM fungi compared to unseeded treatments;

The combination of both plant seeds and native soil inoculum would result in the highest diversity of both plants and AM fungal communities compared to the addition of either alone; and

Inoculated treatments would lead to a different plant community composition compared to uninoculated treatments.

By measuring the composition of plant and AM fungal communities, we aimed to gain insight into the effects of these treatments on the establishment and development of plants and AM fungal communities in post-industrial landscapes.

2. Materials and Methods

2.1. Study Area

The object of research is the types of soil of Yavoriv SMCE "Sirka" formed as a result of its activities in the sulfur quarry, which is located in the Lviv region (Ukraine), within the Yavoriv mining district. The Yavoriv sulfur quarry is located in the main European watershed that separates the Baltic and Black Seas. The distance to the State border with Poland is about 20 km. The area is at the junction of the Eastern European platform with the Pre-Carpathian marginal depression. The geological section is based on terrigenous Cretaceous deposits, and the carbonate–sulfate stratum rests on them. Part of it is replaced by sulfur ore, which forms in an elongated manner along the edge of the platform deposits up to 30 m thick, up to 4–5 km wide, and up to 20 km long. Neogene clays and marls from 30 to 250 m in thickness lie above sulfur ores. They have washed valleys of ancient rivers, filled with alluvial and lake sand–clay deposits. Sulfate–carbonate stratum and sulfur ore of various degrees of karstification contain hydrogen sulfide water with a salinity of 3–5 g/L. Quaternary sediments are also flooded. The main rocks developed by the method of hydromechanization are stored in a hydraulic dump. These are mainly fluvioglacial and alluvial deposits, represented by sands, sandstones, loams and clays. The hydraulic dump consists of three parts: sandy, argillaceous and calcareous. About 70 million tons of small fractions of hydraulic disclosure, represented by sandy loam and clay loam and scattered organic matter from peat, are accumulated in its central part. These formations are characterized by high humidity and low moisture yield, so their drainage is almost impossible. They remain in a fluid or soft-plastic consistency for decades. Because, during the operation, the hydraulic dump sometimes came across the water from the reverse system of the concentrator, the water there was sulfate and weakly mineralized. Gradually, it was replaced by rainwater, and in 2022, water in the hydraulic dump lake had a total mineralization of 506 mg/L, including 247 mg/L of sulfates [25–31]. There are three artificial hills around the quarry—the external dumps. Dumps No. 1 and No. 2 are composed of Neogene marls and clays, poured mainly by heap-forming rotor complexes. The surface of dumps, except for technological roads, has a ridged or hilly relief. Dump No. 3 is composed of Neogene and Quaternary rocks during the excavation of the cut trench [26].

2.2. Determination of the Main Forestry and Taxation Indicators

The laying out of experimental trial areas to determine the main forestry and taxation indicators of experimental forest stands was carried out in accordance with the methodology of conducting field research using the field geographic information system Field-Map. Before starting the measurements on the trial area, its coordinates were fixed using the Magellan eXplorist—a 100 GPS receiver in the UTM coordinate system, with subsequent transfer to the appropriate system for displaying the area on space photographs, maps or plans. The azimuth and distance to each tree were measured directly on the test area using the Map Star System electronic compass and the Tru Pulse Laser Technology laser range finder (which were later converted into rectangular coordinates in the software product, taking into account the angle of inclination). Tree placement data are graphically displayed on a computer monitor and automatically stored in a file database.

2.3. Mycological Soil Analysis

For the mycological analysis of the Yavoriv sulfur quarry territory soil, seven stationaries were selected and established, from which soil samples were taken for mycological analysis during 2008–2021 in April, July and October of each year. Soil samples were taken in the surface layer at a depth of 0–5 cm. Separation of micromycetes from soil and root washes was performed by dilution [32–42]. Cultivation of the studied samples was performed at a temperature of 26–28 °C. Isolated cultures were studied in a light microscope MBI-6 according to the method adopted in mycological research [43]. The experiment was repeated three times. Determination of isolated fungi was performed according to generally accepted determinants [44–46]. To assess the ecological status of soil mycobiota, the frequency of microscopic fungal species, the Sorensen–Chekanovsky coefficient and the mycobiota melanization index were taken into account [47,48].

The number of micromycetes was expressed in CFU units (colony-forming units) per 1 g of soil or mass of raw material. The identification of selected fungi isolates was carried out according to micromorphological and physiological and cultural characteristics, using identifiers. The systematic belonging of micromycetes was determined according to the published 10th edition of "Ainsworth and Bisby's Dictionary of the fungi" [49] and, in some cases, according to other modern literary sources.

The sample was sieved before applying the soil sample to the nutrient medium. Next, we inoculated the obtained soil suspension on the nutrient medium and kept these samples in a thermostat for 20–30 days at a temperature of 25–27 °C. Fungi colonies were counted after three days and a week, and they were separated into a pure culture. Cultures were stored at a temperature of 4 °C. Identification of isolates was performed on standard nutrient medium based on their morphological and physiological characteristics [50–52].

2.4. Determination of Physiological Parameters of Plants

Physiological indicators of plants were determined using the ecological and physiological method, namely, drought resistance—by the starch test method, salt resistance—according to Henkel, and gas resistance [53].

The growth and development of plantations on the quarry dumps were studied using the arboricultural and taxation method [54], and the types of forest vegetation conditions of the flora are given in [55,56].

Geobotanical descriptions of test areas were carried out according to standard methods [57]. The size of the test plot for the study of grass coenoses varied from 4 m^2 to 100 m^2. In the study, we used plots of 4 m^2, which were laid out in three large plots [58]. O. Drude's scale was used to assess the aboveground vegetation cover. The taxonomic analysis of the plant cover was carried out according to the system of A.L. Takhtadjian (1972). Plant associations were determined according to the method of V.V. Alyokhin (1928) [59], based on the dominant species in each tier [60,61], and E. Ya. Yelin.

Determination of the growth characteristics of fungi was carried out by surface sowing of the studied species in the environment of Chapek. Crops were sown by injection into the center of a Petri dish. The cultivation time was 14 days, and the cultivation temperature was 24 °C. The experiments were performed with inoculation on Chapek medium with sucrose and without sucrose. After 48 h of incubation at 24 °C, the diameter of the colonies grown on the plates was measured using a ruler. This operation was repeated every two days for two weeks. The arithmetic mean was taken as the diameter of a single colony at a particular point in time.

2.5. Determination of Ecological and Systematic Analysis of the State of Soil Microbiota

An ecological and systematic analysis of the state of soil mycobiota was determined using relevant ecological indicators: the frequency of micromycetes occurrence, the Sorensen–Chekanovsky similarity coefficient, the Shannon diversity coefficient, the Simpson dominance index and the mycobiota mechanization index. They are the main universal indicators of the reaction of biota to various influencing factors [62].

The frequency of occurrence of a species is calculated using the formula:

$$C = \frac{A}{B} \times 100 \tag{1}$$

where C—the frequency of occurrence, %; A—the number of samples in which this species was detected; B—total number of detected samples.

If the frequency of occurrence of microscopic fungi is more than 50%, then we consider that these species are dominant; if 30–50%—those that occur often; and occurrence at the level of 10% and less—rare species.

To compare the degree of similarity and difference of the list of species of microscopic fungi isolated from different soil, we use the Sorensen–Chekanovsky coefficient:

$$S = \frac{2C}{A + B} \tag{2}$$

where S—the Sorensen–Chekanovsky coefficient; C—number of common mushroom species for two items; A and B—the total number of mushroom species isolated from the first (A) and second (B) points of the study.

We also calculate the coefficient of biological diversity (Shannon coefficient)—the higher this coefficient, the more diverse the species composition of microscopic soil fungi:

$$H = -\sum p_i \log \log_2 p_i,\ p_i = \frac{n_i}{N}, \tag{3}$$

where H—Shannon coefficient; p_i—probability of significance for each fungal species in a specific soil type; n_i—the importance of each type of fungus in a certain type of soil; N—the importance of all types of fungi in a certain type of soil.

Simpson's dominance index is calculated using the formula:

$$C = \sum (n_i/N)^2 = \sum (p_i)^2 \tag{4}$$

where C—Simpson's dominance index; p_i—probability of significance for each fungal species in a specific soil type; n_i—the importance of each type of fungus in a certain type of soil; N—the importance of all types of fungi in a certain type of soil.

In order to substantiate the potential model of restoration of sulfur quarries of the Lviv region over a significant period of time (2008–2016) and to compare the main ecological indicators of the mycobiota of sulfur quarries of the Lviv region, the data of the main ecological indices of Podorozhnie quarry were determined by the researcher U. R. Nazarovets [63]. The color of the colonies, which is necessary for the description of the isolates, was determined using the Bondartsev scale and using the additive RGB model of Adobe Photoshop CS5.

Native soil inoculum for the experiment was produced in a greenhouse using a trap-culturing methodology. In trap culturing, AM fungi are grown together with host plants in a low-nutrient substrate to induce AM fungal colonization of plants and spore production among AM fungi, effectively propagating an inoculum. Target community soil was collected from a mine spoil area restored with topsoil (49.9492° N, 23.4675° E) and exhibited a diverse grassland plant community. Thirty cm of topsoil was collected from six locations at the site and pooled. The soil was mixed with sieved sand (<2 mm) and gardening substrate at a ratio of 2/7/1. The soil was divided into 4 L growing containers and sown with the same seeding mixture (see Section 2.3) that would be used in the field experiment. Pots were maintained for 18 weeks, after which they were taken outside, covered and subjected to winter conditions for 1 month to ensure a natural vernalization period for the fungi. Then, the aboveground plant material was removed, and the soil were transported to the sites where one 4 L container was used as inoculum for each 4 m^2 plot.

Gardening substrate was not sterilized prior to trap culturing. The gardening substrate was, however, checked for AM fungal propagules by growing the same mixture of plants for 18 weeks on only the gardening substrate (no natural soil added), followed by staining with trypan blue and microscopical examination of the roots. The plants grown only on gardening substrate did not exhibit any signs of mycorrhizal fungal colonization (n = 5).

2.6. Preparing the Inoculum

The experimental micromycete *O. echinulatum* was grown in Chapek environment. The composition of the medium (g/L): KCl—0.5, $MgSO_4$—0.5, KH_2PO_4—1.0, $FeSO_4$—0.01, (1 mL of 1% solution). As the fungus was isolated from areas where the sulfur content exceeded the norm by 10 times, the amount of $FeSO_4$ was increased to 0.1, i.e., 10% solution,

$NaNO_3$—2.0, sucrose—20.0, H_2O distilled; pH—7.0. The labeled ^{35}S sulfur isotope was introduced into $FeSO_4$ into the medium where the fungus was grown. The method of isotopic indicators used was based on the position that the chemical properties of different isotopes of one element are almost the same, so their behavior in the studied processes does not differ from the behavior of other atoms of the same element; secondly, radioactive isotopes in quantities used as a label do not have a biological effect on living organisms. Thus, it was possible to observe the migration and accumulation of sulfur in the fungal culture. The resistance of the micromycete *O. echinulatum* is due to the presence of melanin, which has shown active properties as an energy transporter for metabolism. The procedure was as follows: the liquid nutrient medium was poured into flasks at 1/4—Vs volume and, after sterilization, was inoculated with a wash of 5–7-day culture from beveled agar, with complete spore formation. Inoculated flasks were placed in shaker at a temperature of 28–30 °C and at 105 rpm. The liquid medium was sterilized through Schott G-5 glass filters. Molds were transferred from a dense nutrient medium to a fresh liquid medium with a bacterial loop in the following order: After calcination of the bacterial loop, it was cooled and, capturing a small number of mold spores from mature culture, transferred to the nutrient medium in flask, conducting a loop on its surface from the lower edge of the medium to the upper. The bacterial loop with the spores captured by it was immersed in the liquid medium and placed for growth. Given the fact that the half-life of the isotope ^{35}S is 87.1 days, the fungus was grown for 90 days. Observations were performed every 2 days. Tril-Carb 2800 TR Liquid Scintillation analyzer liquid scintillation counter from Carl Zeir was used to quantify the labeled element. The experiment was performed in the laboratory of the Department of Physiology and Systematics of Micromycetes of the Zabolotny Institute of Microbiology and Virology of the National Academy of Sciences of Ukraine. Sulfur compounds are known to accumulate in the fungal cell wall and cytoplasm.

An experiment on growing planting material was conducted in a semi-controlled environment. Seedlings of trees and shrubs common in phytomelioration were used: *Quercus robur* L., *Pinus sylvestris* L., *Betula pendula* Roth., *Sorbus aucuparia* L., *Prunus divaricata* Ledeb., *Robinia pseudoacacia* L., *Hippophea rhamnoides* L. and *Rosa canina* L. In the experiment, the roots of the plants were inoculated with a spore remedy of mycorrhiza. Seedlings planted without inoculation served as control.

The reclamation role of inoculation of seedlings of trees and shrubs with arbuscular mycorrhizal (AM) fungi on their survival and growth on sulfur-containing human-made soil of the Yavoriv sulfur quarry was studied during two growing seasons in semi-production conditions by planting seedlings in boxes selected on embryozems. Care of seedlings and measurement of their morphometric indicators of growth and development was carried out during the growing season. The growth and development of planted seedlings were assessed by the survival of plants and their growth in height during the first and second years of cultivation.

2.7. Construction of Correlation Pleiades and Dendrograms of Group Similarity

The method of correlation pleiades is used to identify correlational signs between species of micromycetes and signs of the external environment, in particular, the soil conditions of Yavoriv sulfur quarry. The method consists in calculating pairwise correlations between features and building a conditional model of the "correlation cylinder", the perpendicular axis of which is graduated from the bottom to the top by the value of the correlation coefficient. The correlation cylinder was conventionally divided into different levels (r = 0.1; r = 0.5, etc.), where a "correlation ring" was obtained at each dissection. They placed the signs in a circle, connected them with chords, and obtained a graphic representation of the fungal complexes that formed in the studied types of soil [64]. At the zero level, all characteristics typical for the grouping are always interconnected. As the level of dissection increases, more and more connections fall out. Pleiades will gradually emerge, and this process is specific to a particular population. Its speed is measured by the ratio of the number of connections that remained to the total number of connections between features (E is the coefficient of homogeneity). The level at which the pleiades are understood served as a degree of homogeneity or integration [65]. We determine the frequency of occurrence for each of the selected genera (species) of the studied ecotopes. The construction of correlation constellations is carried out taking into account the type of soil and seasonality. Graphically, the results are presented in the form of dendrograms and correlation pleiades. This makes it possible to identify structural genera (species) that are responsible for the formation of a specific fungal complex.

The method of principal components was used to identify the relationship between the frequency of occurrence of species and artificially transformed soil for cultivation using multivariate statistical analysis. The essence of the method is that the matrix of paired correlation coefficients between features in the sample, after the appropriate transformations, makes it possible to calculate the matrix of values and the corresponding matrix of vectors. The eigenvalues in the sum determine the total variance of the features of the original matrix. Each value determines the contribution of the corresponding principal component to the total variance. Each principal component is a linear combination of initial features (species):

$$F_i = \frac{1}{S_i \times \sum_{j=1}^{n} a_{ji} \times y_j},\ i = \overline{1, m} \tag{5}$$

where F_i—the first principal component; a_{ji}—weight factor of the first feature in the first principal component; y_j—serial numbers of features; S_i—eigenvalue of the first principal component.

At the same time, each feature is represented through the main component:

$$y_i = \sum_{j=1}^{n} a_{ji} \times f_j,\ \ i = \overline{1, m} \tag{6}$$

We determine the weight coefficients of the connection of features u_i with the main components by the formula $a_{ij} = u_{ij} \cdot f_j$, where u_{ij} is the value of the eigenvector for the i-th main component.

The total number of main components is equal to the number of features in the sample, but for further analysis, we use only those main components whose total contribution to the total variance is the maximum. We consider the obtained results in the coordinates of two main components, where the weighting coefficients of the connection of features with these main components determine the corresponding points of the feature on the plane. In the future, we would pay attention to those signs (in our case, species) for which the weight factor is greater than 0.7.

The coefficient of determination r^2 shows how much the degree of relatedness in the variation of one characteristic of the species being studied is explained by the change of another, and the last part of the variations is either mutually independent or depends on factors that are not taken into account. The analogy is given on the basis that: for $r > 0.85$—the connection is very strong, for $r = 0.70–0.85$—the connection is strong, for $r < 0.7$—the connection is weak.

3. Results and Discussions

Vegetation formation on the devastated lands of Yavoriv SMCE “Sirka” is primarily due to the intensity of soil-forming processes. Landscapes of territories disturbed because of native sulfur extraction are formed due to the transformation of autochthonous soil cover: mechanical (storage of host and overburden, arrangement of tailings), physical (deformation of the meso-relief, change of soil structure during hydromechanization) and chemical (pollution by waste and emissions in areas of underground sulfur smelting, flotation of sulfur-containing rocks) (Figure 1).

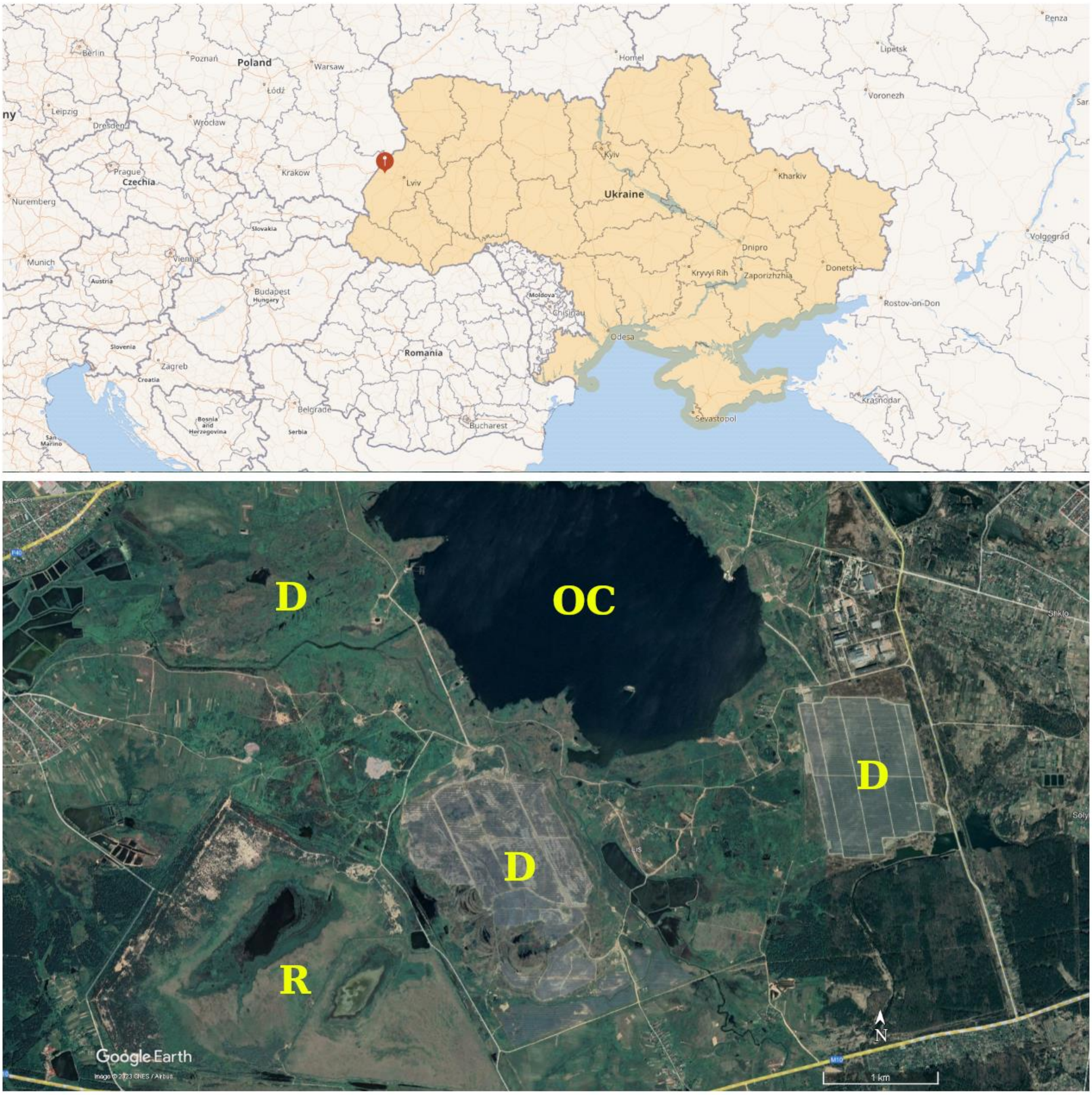


Figure 1. General and detailed scheme of Yavoriv SMCE "Sirka": OC—open cast, Yavoriv quarry; D—dumps; R—reservoir of industrial water [66,67].

A special case is the formation of a succession series of post-industrial biogenic-undeveloped soil, which are confined to areas of underground sulfur smelting, formed on substrates of sandy and cohesive-sandy composition and which are close in particle size distribution to soil-forming rocks of sod-podzolic soil as noted in the works of Kopii et al., Taras, Vinohradov and Turekian et al. [63,68–72]. These embryozems belong to soil contaminated with a high content of mobile sulfur sulfate 370–2403 mg S-SO_4 kg^{-1} (MPC of mobile sulfur for soil is 160 mg S-SO_4 kg^{-1}). In such soil, the diagnostic horizon Sh, which testifies to the existence of highly toxic concentrations of chemical compounds, is allocated. The areas that are recultivated with the introduction of soil substrate are timed with techno-soil, which are divided into types: technosol undifferentiated and differentiated depending on the time of their operation. According to [73], technosols belong to two types in terms of content and quality of organic matter (organic and humogenic), and two types in terms of bulk horizon capacity (low-power and normal).

The flora of the devastated lands of the Yavoriv sulfur quarry includes 155 species of higher plants, which belong to one division, five classes, 35 orders, 38 families and 104 genera. In the hierarchy of taxa, the leading place belongs to angiosperms (22 orders, 24 families, 74 genera and 108 species). The family *Asteraceae* (21 genera, 30 species) is characterized by the greatest species diversity. The second and third places are occupied by the families *Rosaceae* and *Salicaceae* (respectively, 8 genera, 12 species; 2 genera, 11 species). The first six families include 73 species, which is 67.59%, and 45 genera, which is 60.81%. Two families of angiosperms (*Polygonaceae* and *Scrophulariaceae*) are represented by four species, one family—three species, five families—two species. Fourteen families (or 18.92%) in the studied flora are monoecious. Within the types of plant groups we have selected, the species structure is quite diverse, which is again indicated by the diversity of edaphic conditions.

The studied flora is dominated by 132 species of herbaceous plants (85.16%), with herbaceous monocarpics numbering 98 species and polycarpics numbering 34 species. The group of woody plants is insignificant—23 species, 14.84%. The ratio of herbaceous polycarpics to herbaceous monocarpics is 1:2.8, while the ratio of woody plants to herbaceous is 1:5.8. The flora of embryos of the Yavoriv sulfur quarry is characterized by the dominance of herbaceous vegetation with an admixture of woody plants. By type of root system of flora, plants of rod–root and rhizome types predominate, respectively, 72 (46.47%) and 38 species (24.42%). This structure indicates the initial stages of the formation of primary vegetation.

According to the method of seeds spreading among plants of the adventitious flora of the Yavoriv sulfur quarry, apochors predominate—92.62. These are plants whose fruits and seeds are transported under the influence of various additional forces. The share of autochors (plants that distribute fruits and seeds with the help of specific means without the influence of external agents) is 7.38%. Wind and animals play a significant role in the reproduction of plant rudiments. The influence of the human factor on the processes of self-healing by adventitious flora is insignificant.

Advent florocenocomplexes on quarry embryozems are represented by nine groups: agro–ruderal, meadow–steppe, forest–shrub, hydrophilic, meadow, meadow–swamp, forest–meadow and shrub. The predominant species are representatives of agro–ruderal (21 species), meadow–steppe (14 species) and forest–shrub adventitious flora. The high proportion and activity of weed species are indicators of incomplete demutation processes.

It is established that seven micromycetes belong to the typical dominant species in the post-industrial landscapes of the Yavoriv sulfur quarry. These are, in particular, species with spatial and temporal frequency in %: *Oidiodendron echinullatum*—73, 74; *Cladosporium cladosporioides*—66, 70; *Trichoderma lignorum*—88, 61; *Trichoderma viride*—63, 68; *Trichoderma terreus*—65, 68; *Penicillium citrinum*—72, 70; *Aureobasidium pullulans*—77, 54. Eight species of soil fungi have been identified as typical frequent micromycetes. These are, respectively, in %: *Penicillium brevicompactum*—58, 51; *Aspergillus fumigatus*—53, 48; *Fuzarium oxysporum*—58, 50; *Humicola grisea*—49, 41; *Zugomicets sp.*—46, 40; *Monilia cinerea*—36, 38; *Rhizopus oryzae*—35, 45; та *Aureobasidium tenuisima*—31, 40. Fifteen species of fungi are dominant and common, forming the basis of structural features of devastated soil.

According to the results of the generalization of plant descriptions on the studied embryos of the Yavoriv sulfur quarry, the following types of phytocenoses have been identified: swamp–ruderal, swamp, meadow–swamp, meadow, shrub–meadow–ruderal, shrub and forest. Each of the observed types of phytocenoses is characterized by its specific characteristics regarding the microrelief of the formation, the mechanical composition of the soil substrate and the impact of negative anthropogenic and environmental factors. A specific type of phytocenosis is characterized by a specific horizontal and spatial structure of the location in the space of plant components.

The analysis of the forest lands adjacent to the territory of the Yavoriv sulfur quarry indicates that two types of forest vegetation conditions prevail here: fresh snowdrift;

confined to flattened and slightly convex relief forms; and wet snowdrift of a lumpy subtype, common on slopes and lowlands. In these types of forest vegetation conditions, the following plantations of forest types are formed [74]: fresh oak–pine subtree, moist beech–pine subtree, moist beech–pine subtree of a lumpy subtype and fresh hornbeam–pine subtree. According to the age structure of the plantings, mostly conditionally age-old, they are characterized by stands with three tiers. Stands are high-quality, especially in fresh heaps of the busty subtype, where pine and oak reach site class I.

An important task of coenotic research within anthropogenically disturbed areas, in open and underground sulfur extraction, is the study of fungal successions in self-restoration and reclaimed areas [75–77]. As noted in Pohrebennyk et al., Liu et al., Kochan et al. and Andriiuk et al. [6,26,78,79], fungi play an important role in the transformation of organic compounds: the decomposition of cellulose, lignin and pectin and the Nitrogen cycle, in particular in the processes of ammonification, which contributes to the formation of conditions for the development of other microorganisms. In addition, soil fungi are able to produce a variety of biologically active substances: amino acids, enzymes, lipids, polysaccharides, antibiotics, plant growth stimulants, vitamins and toxic substances [63,80].

During the summer, 11 soil samples were taken within the Yavoriv sulfur quarry, of which about 5391 fungal isolates were isolated.

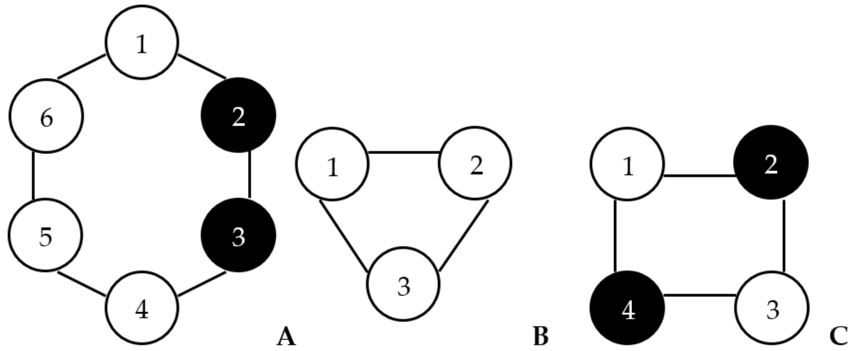
Based on the calculations, the main complexes of micromycetes formed on zonal soil (Figure 2) and on embryozems of the Yavoriv sulfur quarry (Figure 3) were determined. The zonal type of soil includes soil in the distribution of which the latitudinal zonation on the plains and high-altitude zonation in the mountains can be clearly seen in the land area [81]. According to this pattern, the following types of zonal soil are distinguished: red, yellow, brown, gray and brown desert, chestnut, chernozems, brown forest, gray forest, podzols and sod–podzols, tundra gley, arctic [82]. The highest fertility are chernozems formed in loess (loose rocks, which are the result of glacier activity); the lowest—arctic soil [81–86]. As noted by Dong et al. [84], a reliable indicator of environmental conditions can be a specific set of species of micromycetes, the characterization of which requires the use of quantitative criteria.

The results of the correlation analysis of the micromycete biota of each of the ecotopes during 2019–2021 showed that primitive complexes were formed in embryozems, which mainly consisted of light-colored species. All of them were formed at a high level of similarity r = 1.0; 0.95; 0.89 (Figure 3A–C) and are classified as closed, three-membered and linear. Structural for the pleiades were the genera: *Oidiodendron*, *Penicillium*, *Aspergillus* and *Trichoderma*.

Stable fungal complexes have also been found in zonal soil. Correlation pleiades, which reflected their structure at the level of r = 1.0, belonged to the types of “star-grid” and “square” three-membered pleiades (Figure 3A–C). Fungal complexes of zonal soil were characterized by a predominance of structural light-colored *Penicillium ochro-chlorum*, *F. oxysporum*, *Aspergillus niger*, *T. lignorum*, *Paecilomyces lilacinus*, *P. citrinum* and *T. terreus* species. Some species of melanin-containing genera of fungi were included in the fungal complexes of zonal soil, in particular, *C. Cladosporioides* and *A. niger.*

Analysis of the material by season showed that the most stable fungal complexes are formed in all ecotopes during the summer months. The formation of stable fungal complexes in embryozems with high sulfur content indicates a structural reorganization of soil microbiota. As a result, highly organized micromycete complexes have formed in embryozems, in which light-colored species play a leading role.

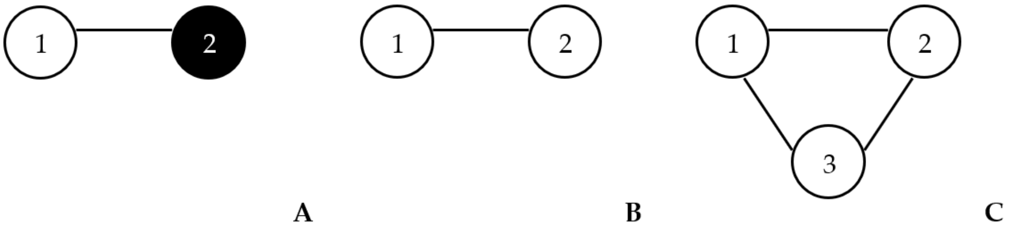
In general, the formation of stable fungal complexes with a high content of specific species of fungi in extreme ecotopes under the conditions of existence confirms their significant resistance to such influences.



A: (*1*). *Penicillium ochro-chlorum*
(*2*). *Cladosporium cladosporioides*
(*3*). *Aspergillus niger*
(*4*). *Penicillium citrinum*
(*5*). *Trichoderma terreus*
(*6*). *Fuzarium oxysporum*
C: (*1*). *Penicillium brevicompactum*
(*2*). *Cladosporium cladosporioides*
(*3*). *Trichoderma lignorum*
(*4*). *Aureobasidium tenuisima*

B: (*1*). *Fuzarium oxysporum*
(*2*). *Trichoderma lignorum*
(*3*). *Paecilomyces lilacinus*

Figure 2. Complexes of soil organisms formed on zonal soil types. (**A**–**C**)—complexes of soil organisms formed on zonal soil types. The black circle is the dark-colored fungy species, the white circle is the light-colored fungy species.



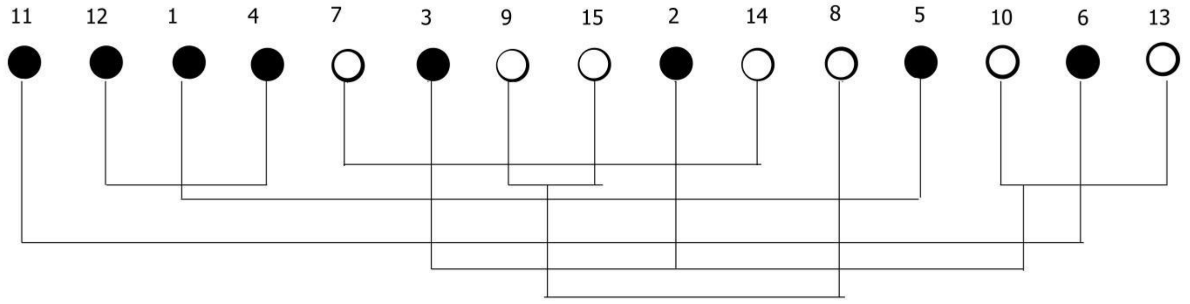
A: (*1*). *Oidiodendron echinullatum*
(*2*). *Aspergillus niger*
C: (*1*). *Trichoderma lignorum*
(*2*). *Trichoderma viride*
(3). *Oidiodendron echinullatum*

B: (*1*). *Penicillium citrinum*
(*2*). *Oidiodendron echinullatum*

Figure 3. Complexes of soil micromycetes formed on embryozems. (**A**–**C**)—complexes of soil organisms formed on zonal soil types. The black circle is the dark-colored fungy species, the white circle is the light-colored fungy species.

As noted in John et al. [87] and Caracava et al. [88], to study the ecological role of individual plant species in the formation of mycological coenoses in disturbed lands of the Yavoriv sulfur quarry, it is important to note the mycological structure of soil in areas with varying degrees of revitalization.

Analyzing dendrograms of group similarity, which are also built based on correlation analysis, it is necessary to note a strong correlation between melanin-containing micromycetes in human-made soil. At a high level of significance (of the order of 90–100%), nine–twelve species of fungi were united by close correlations, seven of which belong to melanin-containing (Figure 4).



1	*Aureobasidium*	6	*Alternaria*	11	*Botrytis*
2	*Cladosporium*	7	*Mucor*	12	*Rhizopus*
3	*Phoma* sp.	8	*Fusarium*	13	*Acremonium*
4	*Phoma pomorum*	9	*Aspergillus*	14	*Mortierel*
5	*Phoma glomerata*	10	*Penicillium*	15	*Trichoderma*

Figure 4. Dendrogram of group similarity of fungi on zonal soil. The black circle is the dark-colored fungy species, the white circle is the light-colored fungy species.

The closest connections in the dendrogram characteristic of technosol were observed among the species of the genera *Phoma*, *Alternaria*, *Aureobasidium* and *Cladosporium*, belonging to the family *Dematiaceae* та *Mucor*, *Aspergillus*, *Trichoderma*, *Fuzarium*, *Penicillium*, *Mucor* and *Rhizopus*—members of the genus *Moniliaceae*. In the dendrogram, which reflects the structure of the fungal group characteristic of embryozems, 15 genera are united. At a high level of similarity, the same species of fungi of the Dematiaceae family as in technosols were grouped into clusters.

This quantitative approach to the analysis of micromycete complexes allowed us to identify characteristic fungi for different soil types, and to show the specifics of microscopic fungi for each soil type; for example, their affiliation to the law of geographical zonal distribution of microorganisms. It is shown that by changing the complex of typical species of micromycetes, it is possible to assess various anthropogenic influences, increase the presence of phytotoxic species to establish their role in soil toxicosis and identify species that are characteristic of specific soil conditions and plant successions. The complex of typical species proved to be an important characteristic of the soil and, at the same time, a tool for solving issues related to soil genesis, determining the degree of the anthropogenic impact on soil and screening problems of producer strains.

On embryozems, there is an increase in phytotoxicosis compared to zonal soil, which is accompanied by suppression of development. Both the abiogenic factor (accumulation of pollutants) and the biogenic factor (accumulation of micromycetes) are involved in the development of the phytotoxicosis of embryozems.

The results of the calculations of the ecological diversity indices of soil micromycete groups of the Yavoriv sulfur quarry monitoring sites are summarized in Table 1.

The value of indicators of the structure of complexes of microscopic fungi for both types of soil indicates the presence of significant differences between zonal soil and soil disturbed by sulfur extraction. Similarly, the Shannon, Simpson, and Pislu indices are higher on zonal types. The maximum values of species diversity were recorded in 2020, which confirms the self-healing functions of quarries and the restoration of natural communities.

Table 1. The ecological diversity indices of soil micromycete groups of Yavoriv sulfur quarry monitoring sites.

Types of Soil	Season	N	Sorensen Species Diversity Index	Simpson	Types of Soil	Season
Embryozems	2019	21	9.34	0.011	1.02	0.38
	2020	24	9.47	0.014	1.03	0.34
	2021	27	11.24	0.102	2.37	0.73
Zonal soil	2019	35	13.56	0.087	2.76	0.79
	2020	40	16.64	0.066	3.07	0.79
	2021	41	16.91	0.068	3.12	0.84

Species diversity of mycelial micromycetes increases during the transition from phytoplanes to litter and the upper mineral horizon of soil. These patterns are consistent with the functionality of mycelial micromycetes (the presence of a wide range of hydrolytic and other enzymes that allow the utilization of various compounds, including those inaccessible to other microorganisms); mycelial type of growth, which allow the successful carrying out of the colonization of various substrates; and the highly xerophytic and rather expressed thermotolerance of microscopic fungi.

Previous studies in the areas of the sulfur quarry were characterized by a high content of melanin-containing species of *Deuteromycetes* in the structural genera of correlation pleiades [68,89]. The restoration of soil mycoflora, in turn, contributes to the restoration of vegetation and the formation of a stable phytocenosis [68].

Accelerating the process of restoring the natural productivity and ecological functions of the forest close to nature is a possible measure for inoculation with a remedy based on mycorrhiza [64]. To identify the properties of symbiotic fungi, edatope was stabilized under conditions of a high content of sulfur compounds in the soil. Peculiarities of sulfur localization and transformation in *Oidiodendron echinulatum* cells were determined.

To increase the efficiency of soil remediation, plants are used together with microorganisms associated with them. The role of plants in soil purification is related to their ability to absorb and transform toxicants, activate the activity of microorganisms, and, as a consequence, intensify biochemical and chemical processes of conversion of foreign compounds in the soil. At the same time, the activity of rhizosphere microflora and mycorrhizal fungi leads to improved plant development through the production of phytohormones, providing bioavailable micro- and macronutrients, reducing the level of toxic substances in the soil. Known methods of reclamation of disturbed lands involve the inoculation of plant seeds with strains of *Azotobacter chroococum* and *Bacillus megaterium.* The disadvantages of the proposed methods are that it is necessary to order strains of bacteria in specialized institutions and, in addition, there is no data on the ability of microorganisms to adapt to different types of devastated soil and their contamination with toxic substances and their effectiveness [90,91]. Other known methods of reclamation of devastated lands include the use of organic–mineral preparation, which contains peat with microorganisms adapted to the disturbed lands. The disadvantages of these methods include the high cost of production and complexity, as well as the fact that they do not take into account the role of the association of plants with mycorrhizal fungi and do not involve the creation of forest plantations [92]. The closest to the natural method of vegetation restoration is the method of creating durable forest crops on reclamation lands, which includes preliminary soil preparation; planting fast-growing and long-lasting forest crops; and subsequent felling of fast-growing trees, leaving their root system for sprout growth and development. The disadvantages of this method are that it does not ensure the engraftment of plants on soil contaminated with sulfur compounds and, accordingly, their reclamation and remediation are time-consuming, costly and inefficient in creating forests.

The result of the tested approach provides an adaptation of trees to the soil of devastated lands by forming an association of plants and fungi of local mycorrhiza—resistant to embryozem conditions and sulfur pollutants that occur on lands in need of reclamation.

It is noted above that the embryozems of the Yavoriv sulfur quarry are characterized by nutrient deficiency, high content of sulfur compounds, high soil density and other environmental limiting factors. All this contributes to the formation of an unfavorable environment for plant growth and development [93–97].

The results of a two-year experiment on growing experimental plants in two variants—treated and untreated AM fungi are summarized in Table 2.

Table 2. The ratio of survival of meliorative cultures of treated and untreated arbuscular mycorrhizal fungi; times (table fragment).

Species Name of Seedlings	Ratios (Processed/Unprocessed)		
	2017	2019	2021
Q. robur	3.7	4.1	4.3
P. sylvestris	2.5	2.7	2.9
R. pseudoacacia	1.9	2.7	4.0
B. pendula Roth.	2.6	3.2	3.7
P. cerasifera	2.8	3.6	4.5
S. aucuparia	2.2	2.6	2.8
H. rhamnoides	2.4	3.1	4.3
R. canina	2.8	2.9	3.0

After statistical processing of the results, the following was found:

First, we estimate the correlation density by calculating the Pearson correlation coefficient = 0.9, according to Chaddock's table. The survival ratio of *Q. robur* is 81% dependent on seedling treatment with mycorrhizae and 19% dependent on other factors. For the significance level $\alpha = 0.05$, we test the null hypothesis $H_0{:}r = 0$ in accordance with the competing hypothesis $H_1{:}r \neq 0$. We calculate the empirical value of the criterion:

$$T_{emp} = \bar{r}\frac{\sqrt{n-2}}{1-\bar{r}^2} = 0.9\frac{\sqrt{55-2}}{\sqrt{1-0.9}} = 16.365 \tag{7}$$

For a given level of significance and the number of degrees of freedom $k = 55 - 2 = 53$ by using the table of critical points of Student's distribution, we find that $t_{kr} = 1.96$. Since $T_{emp} > t_{kr}$, we reject the null hypothesis H_0 and conclude that the sample correlation coefficient is significant and random variables are correlated. We calculate the confidence interval for the general correlation coefficient:

$$\begin{gathered} \bar{r} - t_{kr}\tfrac{1-\bar{r}^2}{\sqrt{n}} \leq r \leq \bar{r} + t_{kr}\tfrac{1-\bar{r}^2}{\sqrt{n}} \\ 0.9 - 0.05 \ \leq \ r \ \leq \ 0.9 + 0.05 \end{gathered} \tag{8}$$

Confidence interval for the overall survival ratio correlation coefficient for *P. sylvestris*: $0.7 - 0.13 \leq r \leq 0.7 + 0.13$.

Confidence interval for the overall survival ratio correlation coefficient for *R. pseudoacacia*: $0.9 - 0.05 \leq r \leq 0.9 + 0.05$.

Confidence interval for the overall survival ratio correlation coefficient for *B. pendula Roth*: $0.6 - 0.17 \leq r \leq 0.6 + 0.17$.

Confidence interval for the overall survival ratio correlation coefficient for *P. cerasifera*: $0.77 - 0.11 \leq r \leq 0.77 + 0.11$.

Confidence interval for the overall survival ratio correlation coefficient for *S. aucuparia*: $0.6 - 0.17 \leq r \leq 0.6 + 0.17$.

Confidence interval for the overall survival ratio correlation coefficient for *H. rhamnoides*: $0.77 - 0.11 \leq r \leq 0.77 + 0.11$.

Confidence interval for the overall survival ratio correlation coefficient for *R. canina*: $0.3 - 0.2 \leq r \leq 0.3 + 0.2$.

The survival of seedlings of experimental breeds averages of 26.00 ± 2.00% in 2019 and 25.50 ± 1.80% in 2020. The treatment of AM seedlings with mushrooms contributes to a significant increase in seedling survival. Thus, in 2019, the average survival rate of experimental breeds was 79.50 ± 4.56%, and 86.50 ± 3.54% in 2021. That is, the increase in the survival of seedlings of experimental breeds in 2019 averaged 3.1 times, and in 2021, 3.4 times more than in the control. At the same time, it should be noted that the survival rate varied both within a particular breed and in a particular growing season (Table 3).

Table 3. The chemical composition of fungi seedlings of *P. sylvestris* treated and untreated with AM remedy. *F*-statistics and *p*-values are given.

No	Indicator	Seedlings		*F*	Reliability of the Experiment
		Processed	Unprocessed		
1	Raw mass, mg	1242	598	152.437	$p > 0.01$
2	Absolutely dry weight, mg	345	155	35.648	$p > 0.01$
3	Nitrogen, % to absolutely dry weight	1.78	1.88	2.475	$p > 0.01$
4	Nitrogen in one seedling, mg	5.75	2.87	4.368	$p > 0.01$
5	Phosphorus, % to absolutely dry weight	0.185	0.097	0.6158	$p > 0.01$
6	Phosphorus in one seedling, mg	0.60	0.15	0.246	$p > 0.01$
7	Potassium, % to absolutely dry weight	0.66	0.62	0.3478	$p > 0.01$
8	Potassium in one seedling, mg	2.17	0.96	0.981	$p > 0.01$

The obtained results confirm the effectiveness of the method of improving seedling survival and growth in the treatment of mycorrhizal spores with spores of “local” mycorrhiza fungi (*O. echinullatum*), *Suillus luteus* and *Tuber melanosporum*, which significantly activates the survival and growth of trees and shrub seedlings of the sulfur quarry soil.

The results of chemical analysis showed that each mycorrhizal seedling contains significantly more nitrogen, phosphorus and potassium than non-mycorrhizal.

In addition to determining the degree of influence of the treatment of arbuscular mycorrhizal fungi on the survival of forest crops, the study of the effect of treatment of arbuscular mycorrhizal fungi on the growth of seedlings in height was presented. The measurement results of the observations are summarized in Table 4.

Table 4. The effect of treatment with AM remedy mushrooms on seedling growth.

Species Name of Seedlings	Height Increase, cm				Growth of Processed/Growth of Unprocessed, Times
	Unprocessed		Processed		
	h	*p*, 95%	h	*p*, 95%	
Q. robur	4.19	0.37	10.64	0.48	2.5
P. sylvestris	5.02	0.32	10.33	0.38	2.1
R. pseudoacacia	10.71	0.31	31.81	0.87	3.0
B. pendula Roth	13.38	1.04	34.40	1.35	2.6
P. cerasifera	6.76	0.48	22.41	0.44	3.3
S. aucuparia	7.87	0.46	23.29	0.52	3.0
H. rhamnoides	5.99	0.44	14.62	0.42	2.4
R. canina	4.69	0.44	14.54	0.52	3.1

According to the results of these observations, there is a positive effect of the treatment of seedlings with spore preparation AM mycorrhiza (at a high level of accuracy) (*p* 95% < 1.35%). The increase in height gain of the researched rocks averaged 2.7 times compared to the control. In terms of breeds as well as survival, there is a difference in the increase in seedling growth in height. The main reason for this may be the genetic conditionality of a particular breed, which is manifested in the peculiarities of the response to the treatment of mushrooms with the AM remedy. Thus, the growth of seedlings of *P. sylvestris* increased by 2.1 times, *Hippophae rhamnoides* by 2.5 times, *Q. robur* by 2.5 times, *B. pendula Roth.* by 2.6 times, *S. aucuparia* by 3.0 times, *R. pseudoacacia* by 3.0 times, *R. canina* by 3.1 times and *Prunus cerasifera* by 3.3 times. The increase in the height of mycorrhizal seedlings is two to three times higher than the control. In this case, it was found that deciduous species respond to the introduction of the spore drug mycorrhiza more actively compared to *P. sylvestris*. The most intensive treatment of seedlings with AM fungi respond to shrub species and the introducer—*R. pseudoacacia*. Similar data were obtained with the characteristic growth of seedlings in height in the first growing year after transplanting (Table 5).

Table 5. Height of planting material of reclamation breeds treated and untreated with AM mushrooms remedy, cm.

Species Name of Seedlings	**Plant Height, cm**			
	Unprocessed		**Processed**	
	H	***p*, 95%**	**H**	***p*, 95%**
Q. robur	13.76	0.37	20.44	0.48
P. sylvestris	15.64	0.33	21.22	0.34
R. pseudoacacia	31.07	0.33	52.44	0.79
B. pendula Roth.	32.95	0.98	54.18	1.24
P. cerasifera	22.41	0.34	37.90	0.32
S. aucuparia	25.08	0.32	40.58	0.39
H. rhamnoides	20.62	0.33	29.52	0.40
R. canina	14.66	0.31	24.76	0.41

According to Table 5, it is demonstrated that the seedlings of all studied species' height, on average, compared to the control, increased by 55.77%. Within specific species, the growth of seedling height reached the following values: seedlings of *P. sylvestris* by 35.70%; *H. rhamnoides* by 43.11%; *Q. robur* by 48.55%; *B. pendula Roth.* by 61.76%; *S. aucuparia* by 64.43%; *R. pseudoacacia* by 68.78%; *R. canina* by 68.97% and *Prunus cerasifera* by 69.12%.

Mycorrhiza has the maximum impact on the viability of the host plant, exactly where it reaches its greatest development. It is known that in natural conditions, for the root systems of plants of the birch, beech and pine families, mycorrhizal infection is a normal condition [98,99]. Therefore, to obtain data on the functioning of seedlings of mycorrhizal roots, usually, one must compare trees in natural and human-made conditions. Since the statistical survival of seedlings was low on the lands of the Yavoriv sulfur quarry disturbed by sulfur extraction, due to the lack of mycorrhiza formation and obtaining the necessary nutrients for growth, we compared them with artificially mycorrhizal seedlings. Mycorrhiza was found on examination of the root systems of uninfected seedlings that took root in cultures on embryozems. The rest of the uninfected showed signs of lack of nutrients, characteristic of nitrogen starvation, and the simple application of fertilizers did not prevent the death of seedlings. Mycorrhizal plants not only had a better appearance, greater height and weight but also had twice as many short roots. This is due to the stimulation of the formation of short roots, the prevention of death of short lateral branches and the general increase in root size.

4. Conclusions

The restoration of soil cover and plant communities is a critical component of Decision Support Systems for environmental safety management in post-industrial landscapes, as healthy soil and vegetation can help to mitigate the impacts of contamination and promote ecological health. The positive effect of the treatment of seedlings with a spore remedy of arbuscular, mycorrhizal fungi on the increase in growth in the height of the studied breeds, which on average reached 2.7 times higher compared to the control, has been established. The genetic conditionality of a particular breed in response to inoculation with a spore drug is reflected in the difference in seedling growth in height from 2.1 to 3.7 times. Deciduous species are more responsive to the introduction of the spore remedy of mycorrhiza compared to *P. sylvestris*. The height of seedlings of the studied breeds increased compared to the control by an average of 55.77%.

Mycorrhizal plants had a better appearance, two times the height and weight and had twice as many short roots. Similarly, mycorrhizal seedlings contain two times more Nitrogen, Phosphorus and Potassium than non-mycorrhizal.

The conceptual model of inoculation of plants on contaminated soil includes the optimization of the soil environment and improvement of the properties of the soil system, biodetoxification and biodecontamination due to the expansion of populations of soil microorganisms and the use of phytomeliorating plants with a simultaneous effect on the biological and inorganic components of the soil. The possibility of creating phytomeliorating forest plantations on the territory of sulfur quarries is connected with the use of a natural succession of mycomeliorants and the introduction of mycorrhization technologies of planting material of tree and shrub species.

In the process of revitalization of disturbed landscapes through the mycorrhization of planting material within the activities of mining and chemical enterprises, there is a tendency to restore and increase phytodiversity at the floristic and coenotic levels. It was noted that the share of synanthropic species in the process is higher than in the conditions of flooding of free and anthropogenic areas, and the clearing of herbaceous phytocenoses is faster than forest and shrubs, which, due to their durability and leveling properties, have a long period of remediation and formation of typical forest phytocenoses and their phytodiversity.

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