Folia Forestalia Polonica, Series A – Forestry, 2021, Vol. 63 (4), 289–299

ORIGINAL ARTICLE

DOI: 10.2478/ffp-2021-0029

Successive processes at quarry waste dumps of various ages

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Abstract

This work is dedicated to the study of the succession processes in quarries of different ages in the territory of the Russian Federation and neighbouring countries, namely, Kazakhstan and Ukraine. In selected soil samples from the areas studied, certain physical and chemical properties, the quantitative composition of microbial communities and the diversity of floral species from the quarries were studied. The pH values for the Kuzbass area were found to decrease to 4.8, and in the area of the younger quarries – Inguletsky and Sokolovsky – higher pH values were recorded. The basal soil respiration rate of the Kuzbass quarry was approximately 0.2 mg CO_2/g/h. The CO_2 carbonate content ranged from 0.05% to 0.6%. The microbial biomass in Kuzbass soil was from 0.87 to 5.10 µg C/g soil, while its quantity in other quarries was 6 times lower, which is associated with the relatively young age of these sites. The study of the diversity of floral species in the Kuznetsk coalfield identified 120 species of upper plants belonging to 34 families. Among them, cereals, legumes and mosses, lichens and algae were predominant. In the territory of Inguletsky and Sokolovsky quarries, the diversity of plant species was much poorer. In this regard, further research will focus on increasing the rate of succession and maintaining ecosystem stability by increasing the share of microorganisms. Also, the study of the possibility to accelerate the restoration of younger flora in the discharges of age careers at the expense of the mycorrhizal communities formation is of high relevance.

Key words

successional processes, Kuzbass, Inguletsky and Sokolovsky quarries, green cover, physical and chemical properties of soils, microbial biomass

Introduction

Sites such as quarries or mine dumps exist as an inevitable consequence of mining for industry, and therefore represent a growing component of many landscapes and areas. The traditionally negative attitudes of environmentalists towards these sites are rapidly evolving as it becomes clear that in industrialised and intensively cultivated areas, they are invaluable refuges for rare organisms (Talento et al. 2020). Quarries generally contain periodically disturbed, early successional surfaces and are very heterogeneous with extreme abiotic conditions and

Received 8 April 2021 / Accepted 16 August 2021

minimal productivity (Roberts and Mattoo 2018). Such conditions have become rare in modern landscapes because human management activities increase land productivity by promoting half-phase succession over the extreme one. Therefore, in many areas, species dependent on early succession habitats with sparse vegetation are among the most vulnerable (Hattermann et al. 2018). Since quarries and surface mines will remain a significant part of economic activity, succession is expected to maximise the biodiversity potential of mine sites, particularly in densely populated areas. Such sites managed to avoid intensive agriculture, forestry or construction, with the exception of nature reserves (Wang et al. 2018).

It is known that the post-mining restoration method has a decisive impact on the ability of different species to colonise the area and, therefore, on the conservation potential of the restored habitats (Volis 2019). Two different approaches are currently being applied in Central Europe: 1) technical reclamation, which usually consists of covering areas of fertile arable land, then seeding with grass mixtures or planting shrubs and trees and 2) spontaneous succession, usually without direct sowing or planting, but with some suppression of exotic and expanding plants (Prach et al. 2007). Although this last method seems simpler, the first remains preferred due to the perceived need to cure 'scars on the landscape' and prevent erosion and fertiliser runoff, benefiting agriculture, forestry or similar operations (Ahmad et al. 2020).

It is known that the restoration of most quarries is generally slow, and large areas often remain empty after decades of abandonment (Krüger et al. 2017). The main factors limiting plant communities in abandoned quarries are low nutrient availability and unfavourable soil physical properties (Hong et al. 2019). The absence of soil is what defines the first stage of primary succession. Consequently, soil development is the most important aspect of primary succession (Walker and del Moral 2003). A restored community is expected to develop through natural processes without human intervention (Lugo 2020). The restored ecosystem has to withstand stress and include a mixture of native species (Garófano-Gómez et al. 2017). Plant species from disturbed areas grow in stony soils, soils with low nutrient and water content, extreme pH and steep slopes. Because of the severity of soil disturbances in quarries, plant succession is very slow and can take many centuries. Restoration of quarry ecosystem seeks to return it to an earlier state, while reclamation is an act of repairing degraded land (Williamson et al. 2002). Different approaches to reclaiming abandoned pits may lead to differences in biodiversity and ecological functions.

The vast majority of studies on quarries and similar disturbances have examined the effects of seeding or transplantation of different plant species (Wu et al. 2018), including nitrogen-fixing plants such as legumes and alder (Turnbull et al. 2016). Studies reported mixed results. While successful growth of transplanted trees and shrubs is often reported, it is not conducive to ecosystem restoration through colonisation by native species. Introduced species can remain dominant, restoring poorly diversified ecosystems (Wright et al. 2009) or landscapes atypical of the region. Some researchers believe that spontaneous succession regeneration (instead of reforestation) contributes to biodiversity (Schoonover and Crim 2015). Even though natural colonisation in abandoned quarries results in rich and varied flora, the downside is that it often takes a long time before vegetation becomes noticeable (Davis 1982).

Some restoration studies indicate that biodiversity is an important environmental factor for the sustainability of mining (Sonter et al. 2018) and the need for effective practices leading to the restoration of ecological processes and biodiversity. These findings can be extrapolated to other limestone quarries. Restoring a quarry is a complex process – the starting site is generally bare and consists of a low-fertility substrate (Chenot et al. 2018). Therefore, in planning a successful succession process, it is important to identify the best restoration approaches. This includes detailed quantitative case studies, field experiences and comparative studies of large geographical areas (Egli et al. 2018).

Reclamation of quarry vegetation is the principal means of restoring the environment. Restoration of the structural diversity of the plant community may, indeed, improve the diversity of the animal community and the habitat quality and build a relatively comprehensive biological chain to contribute to the restoration of the quarry ecosystem (Zhang et al. 2018). While restorative plants are native species that can grow in poor habitats, but the small number of species, planting a single plant species in a wide range. Ignoring the diversity and richness of the community structure does not encourage plant development or improve the quality of the quarry heaths habitat.

This is particularly important for arid areas, where rainfall is inadequate for the recovery of native flora. Vegetation change in arid regions has been studied very carefully because the sustainable management of natural resources is crucial. In this context, plant–herbivore interaction has traditionally and rightly been regarded as a functionally important ecosystem interaction (Turnbull et al. 2016). This association of organisms is not only important in terms of practical applications, but also provides a basis for the very existence of herbaceous ecosystems in arid areas (Baudena et al. 2015). However, herbivores are not the only significant heterotrophic element in herbaceous ecosystems. Steppes, semi-steppes and, to a lesser degree, desert plants depend critically on their interaction with mycorrhizal fungi. This can be explained by the fact that 60%–75% of steppes and 50%–55% of desert species form the mycorrhizae, mainly of the arbuscular type (Bai et al. 2013). To date, considerable progress has been made in investigating the role of mycorrhizae in vegetation dynamics. Mycorrhizae have been shown to be a specific tool to continuously optimise soil nutrient changes during plant succession, while the result of competition among plants is largely determined by their predisposition and success in interaction with mycorrhizal fungi (Niwa et al. 2018). The general conclusion is that the relationship between plants and fungi tends to increase and the importance of mycorrhizae increases during endoecogenetic succession.

Quarries are an example of severe ecosystem disruption. The total area occupied by mining activities has increased rapidly in recent centuries and continues to do so. Furthermore, mining activities can severely alter pre-existing communities and disrupt hydrogeological and hydrological regimes. Quarries can profoundly alter the soil surface, alter the landscape, destroy natural habitats and interrupt natural succession, and alter genetic resources. Since the issue of the natural ecosystem restoration after such an important anthropogenic load is little studied, it is relevant to examine the characteristics of succession on different types of natural objects.

Given that quarry dumps can vary in age, climatic characteristics and topographic features (i.e., factors affecting flora restoration in a quarry), this paper seeks to investigate quarry succession based on the example of quarries located in Russia and neighbouring countries such as Kazakhstan and Ukraine. To achieve this objective, the following tasks had to be completed:

– selecting different landfills based on age and climatic conditions to study the particularities of their succession processes;
– determining the fundamental physical and chemical properties of the soil in the study areas;
– identifying the quantitative composition of microbial communities in soil samples and
– analysing the diversity of the species of the flora of the quarries studied for their subsequent comparison.

Material and methods

Study regions

The study, conducted during the spring/summer period in 2000–2020, involved three quarry sites. The first quarry site, the Kuznetsk coal basin, also known as

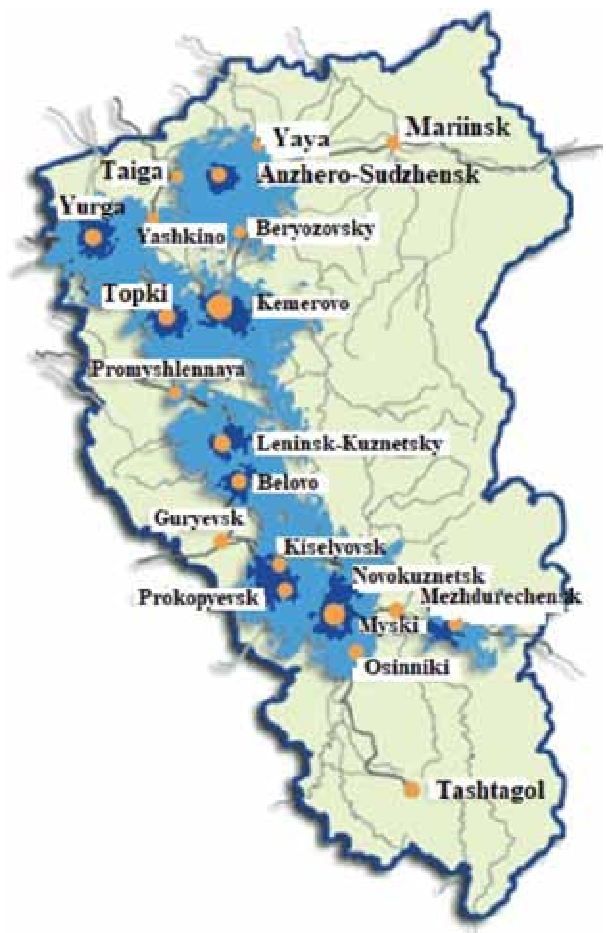

Figure 1. Soil sampling points on the territory of Kuzbass during 2000–2020

Kuzbass (55°21'16"N, 86°05'19"E), is located in Western Siberia, Russia (Fig. 1). It dates back to the year 1721. The climate in this area is strongly continental, with frequent and steep fluctuations in temperature, precipitation and solar radiation.

The main type of vegetation belongs to the southern taiga with conifer forests, but the high frequency of natural and anthropogenic disturbances has led to the formation of small leaf forests. Ecosystems are also characterised by the presence of subboreal floral representatives due to the increased carbonate content in locally sourced materials.

The second quarry site, the Sokolovsky Quarry, is located 45 km southeast of Kostanay, Kazakhstan (Fig. 2). It was discovered in 1948 and operated from 1949 to 1955.

The climate is highly continental, with a pronounced alternation of the four seasons. It has an average annual temperature of 2.8°C. Most of the soil is dark brown and solonetzic. Steppe solonetz on marbled clay with a fine humus-luvial horizon (up to 5 cm) and a thick saline illuvial horizon of cylindrical structure are widely spread in the vicinity of the dump.

The third quarry site, the Inguletsky Quarry, is located in Kryvyi Rih, Ukraine (47°39'25"N 33°10'34"E). At present, it is the biggest quarry in Europe. It was opened in 1955 and is now active (Fig. 3).

The territory consists of steppes and has a moderately warm continental climate, characterised by hot and dry summers and moderately mild winters with frequent thaws. Soils are represented by common black soils, which provide nutrients, contain 4.3%–5.0% humus and are distributed over watersheds.

Figure 2. Soil sampling points at the Sokolovsky quarry (Kazakhstan) during 2000–2020

Figure 3. Soil sampling points on the territory of Inguletsky quarry (Ukraine) during 2000–2020

Sampling

Since small-scale topographical differences strongly influence soil and vegetation succession dynamics (Kim and Kupfer 2016), sites with different topographical characteristics were selected (Fig. 1–3).

In the territory of Kuzbass, soil material was collected in different places (a total of 20 soil samples, the results of which were then averaged). An inventory of the plant life of the quarry has been completed. Plots of 30 × 30 m were created for each ecotype. All plant species, soil mosses, total projective cover and projective cover for each species were determined at each site. Mesomorphological soil description and determination of physical and chemical properties of soils were carried out in the laboratory at the Kazan Federal University. The soil samples were ground and sifted through a 1.5-mm sieve.

The following parameters were determined in the soil samples: water–salt suspension pH (1:3), skeletal fraction content and soil particle size composition by pipetting with pyrophosphate peptisation of microaggregates (Beretta et al. 2014), basal soil respiration, aciometric estimation of CO_2 carbonate content (Dettori and Donadio 2020) and quantification of microbial carbon biomass by spectrophotometry (da Silva et al. 2016). An ecological and phytocoenotic analysis of the vegetation was performed, and the types of life forms were determined according to Coskun (2019).

Statistical analysis

The results were analysed with the MANOVA multivariate variance analysis method using Microsoft Excel and Statistica 10 software. To assess species composition, vegetation similarity at several key sites was calculated using the Sørensen–Chekanovsky coefficient (from De Smith 2018). The differences in the results obtained are likely at the level of $P \leq 0.05$ according to the Student's test.

Results

The main part of the research was carried out in Kuzbass; but for comparative purposes, an examination of other quarries, which are characterised by different geographical conditions and age, was done. Kuznetsk coal basin's quarry is characterised by a variety of landscapes and ecotopes. A wide range of soil surface was found in the quarry, confirming the multidimensional model of ecosystem development. The physical and chemical properties of the soil substrate studied and the results of our mesomorphological studies demonstrate relatively high rates of soil substrate conversion. Organic matter accumulation in surface horizons increased with age, and pH decreased to 4.8 (Fig. 4). A similar trend was seen in younger quarries, Inguletsky and Sokolovsky, although the pH values were found to be higher.

Surprisingly, the lowest pH values were observed in the upper soil layer in relatively high areas of the terrain. All sites were characterised by extremely heterogeneous fractional distribution within the profile. At all locations, large skeletons containing relatively little fine-grained gravel were found. The change in stoniness (from 5.0% on the recultivated plots to 75% on the self-growing background) indicates a high heterogeneity of conditions in the quarry. This indicator is highly dependent on the reclamation technology used.

The high CO_2 concentrations we have recorded are a negative consequence of mining, especially in the case of carbonate rocks. Carbon dioxide emissions in the atmosphere can be estimated from the alteration of carbonates and the basal respiration of the soil (Fig. 4). During the development of soil and vegetation, carbon dioxide emissions are replaced by its sequestration, and the rate of the latter can be estimated from the organic carbon content of the soil. The basal respiration rate in the quarry soil was extremely low (approximately 0.2 mg CO_2/g soil/h). The primary sources of atmospheric CO_2 emissions are altered carbonates. The CO_2 content of carbonate varies from 0.05% to 0.6%, with the highest values being observed in the territory of the old Kuzbass, rather than in younger quarries (Inguletsky and Sokolovsky).

The status of microbial communities in quarries is not well known. This is problematic because microbial communities play a critical role in maintaining community stability and ecosystem development, and in the processes of succession. As a result, studies on the status of the microbial component of habitat are particularly relevant. The microbial biomass in the soil of Kuzbass ranged from 0.87 to 5.10 μg C/g, whereas in other quarries it was 6 times lower (Fig. 5). Although there was no trend in microbiological criteria based on vegetation type or terrain

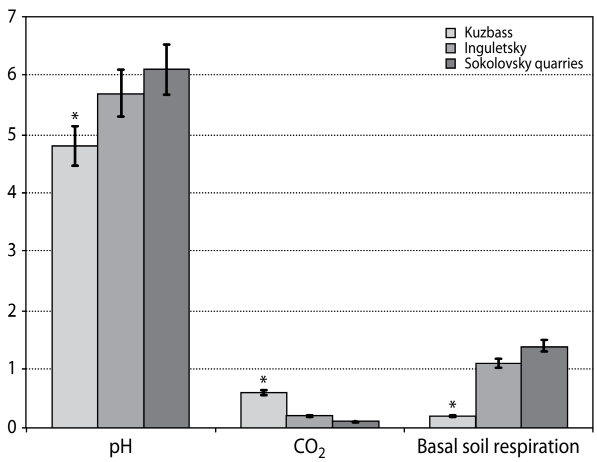

Figure 4. Some physicochemical properties of soil samples in Kuzbass, Inguletsky and Sokolovsky quarries: pH, CO_2 (%) and indicators of basal soil respiration (mg CO_2/g soil/h) *Values are statistically significant at $P \leq 0.05$

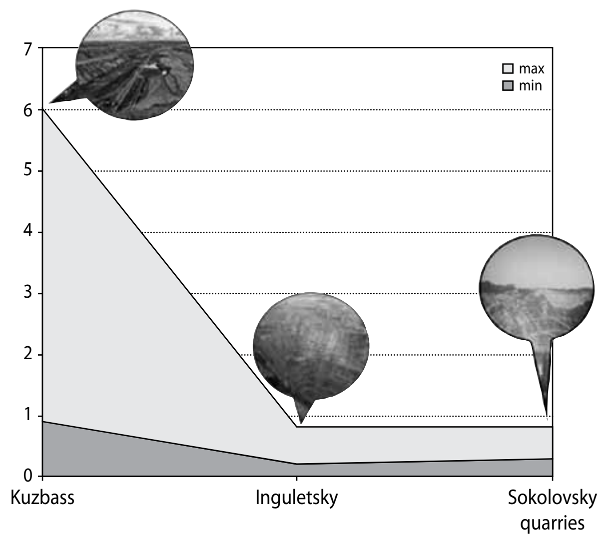

Figure 5. The amount of microbial biomass in soil samples from Kuzbass, Inguletsky and Sokolovsky quarries (μg C/g soil)

shape, values tended to increase with the period of excessive growth.

The Kuznetsk Coal Basin Flora Species Diversity Survey identified 120 superior plant species from 34 families. The families with the greatest number of species included the cereals and legumes (10 species each, or 16% of the total diversity of the site flora). The Asteraceae and Rosaceae had five species each, accounting for about 10% of the identified diversity (Fig. 6). Presence of a large number of legume family representatives is a characteristic feature of disturbed habitats, while the Asteraceae and Rosaceae families are the leading among the flora of the whole Kemerovo Region. The relatively high species richness of the orchid family (five species, 4% of the total number of species), associated with the carbonate substratum of the quarry, attracts attention. The study also identified 5 species of lichens, 15 species of mosses and 63 species of algae.

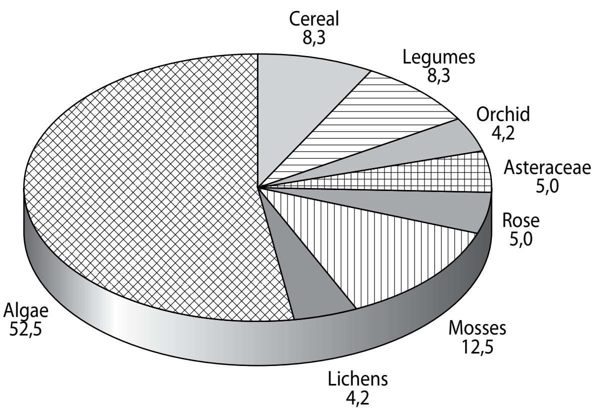

Figure 6. Species diversity of Kuzbass soil flora (%)

The largest similarity of species was observed on the bedrock of the quarry (88%) because it was not enough time for vegetation to restore on this type of soil, which was low in organic matter and moisture. These areas have the most challenging conditions, and only a few species can develop here. The smallest number of common species was found in the zones that occupied different positions in the topography. The lowest species diversity was observed at the Kuzbass site, where pine seedlings were planted on flat ground in 1982. The greatest diversity was found at the newly restored site, where crown closure had not yet occurred, and typical forest species had not yet been displaced by edge species. The results of this study showed that the area with the highest diversity was a quarry waste dump where spontaneous succession had continued for at least 40 years without human intervention. In flat areas, biodiversity decreased as biological regeneration occurred. In areas with spontaneous succession of development (e.g., landfills), biodiversity levels increased. Interestingly, in very rocky zones (large debris deposits and rock bottoms), development was so slow that no significant change occurred in 55 years. This is due to the fact that there was no sufficient time for natural growth of the substratum with algae, which is confirmed by the studies on the territory of Inguletsky and Sokolovsky quarries, where the biodiversity of plants was poorer.

Discussion

The main processes of mineral soil succession are chemical, biochemical and physical alteration of carbonated rocks. The intense alteration of limestone debris contributes to a significant content of fine-grained soils (the only exception is a stony pit bottom), which, in turn, increases the moisture content and fertility (Nguemezi et al. 2020).

Results from these studies showed that the accumulation and acidification of organic matter in soil horizons were the main processes of soil formation in all soils. These processes led to the formation of horizons with maximum thickness and the highest content of organic carbon in the accumulative ecotype with optimal moisture conditions and physical parameters of the substrate. Differences between surface and sub-surface horizons decreased with growing time, which is associated with more intense incorporation of organic matter into the soil profile (Poirier et al. 2020). With the increasing accumulation of organic matter, carbonate acidification and leaching occurred relatively quickly, in particular in the top layer of the Kuzbass soil horizons. However, these processes were less noticeable in other quarries. In small-leaf forests, soil formation processes and horizon formation were similar for accumulative ecotypes, but faster than elusive ecotypes. Most environmental considerations are considered optimal for vegetation growth (Schoonover and Crim 2015). The exceptions were substrates with high densities and excessively compressed bedrock; these properties are impediments to the development of plant communities. Disturbed habitats typically have a large number of plants from the legume and cereal families. At the same time, nitrogen-fixing legumes represent a key component of natural succession. These species are crucial because their symbiosis with rhizobia is a source of nitrogen in the ecosystem (Requena et al. 2001). They also form a symbiosis with mycorrhizal fungi (Zhang et al. 2016). Furthermore, the results of microbial metabolism indicate reduced stability of the microbial community and ineffective use of the organic substrate, especially in the early stages of proliferation (Wu et al. 2018).

The findings from this study are consistent with many quarry studies in different environments and geographical areas, which have shown that deserted quarries can improve biodiversity by providing refuge for plant and animal species (Talento et al. 2020). The diversity of landforms created by mining offers a variety of ecological niches suitable for many plant and animal species, including those of high cultural value (Turnbull et al. 2016).

In this way, abandoned quarries can be considered as tools to create multiple potential niches for different groups of organisms (Talento et al. 2020). According to Spohn (2015), who studied the microbiological status of various quarries, the rate of soil respiration per unit of microbial biomass decreases as the period of excessive growth increases. However, based on the data obtained in this study, it is difficult to determine a trend in microbiological indicators with age. The author also points out that up to 50 years of community life, most microbiological indicators are the same as for undisturbed communities. These findings were reported by Renella (2020), whose results showed that the level of active microbial biomass in sandy soils is slightly different from that of undisturbed soils. However, it is important to note that the assessment methods used in this study are different. We believe that the lowest plant diversity in the Kuzbass quarry was due to the establishment of pine stands in the 1980s, which formed a closed canopy and led to marginal plant varieties displacing the typical forest species. According to the research performed, the microbial intensity of the quarry is very low, regardless of the substrate type, plant community and growing season; this finding is consistent with the findings of the other authors (Tan et al. 2019).

The spontaneous succession of plant communities in quarries with different substrates has been studied in sufficient detail. Most studies have focused on various aspects of vegetation succession (Garófano-Gómez et al. 2017; Hong et al. 2019), and soil formation processes have been analysed in some detail (Egli et al. 2018). However, comprehensive observations of soil and vegetation rehabilitation and connectivity of these components are rare. Regarding the vegetation of the study areas, the data presented prove that the increase in mycorrhizal plants (in particular, legumes and orchids) regularly observed during natural successional processes is effectively repeated during rather rapid primary succession in unfavourable habitats of the man-made dump (Krüger et al. 2017). The ability to accurately date events that have occurred, as well as the development of the studied communities, represents a significant advantage of successional observations on artificial substrates (Lugo 2020). Observations of the development of communities for which the absolute life span (in years) is known have allowed for a quantitative characterisation of the changes in the phytocoenotic importance of plants with different mycorrhizal status. Moreover, the ratio of their abundance was established to stabilise between 15 and 30 years of expansion. The number of highly diverse zones within the territory of the studied dumps is limited because the succession process continues there. In addition, two out of three quarries is too young for changes in vegetation to be noticeable. Thus, if the objective is to maximise biodiversity, creating favourable substrate conditions and avoiding self-financing land is the best way to restore carbonate quarries. It is also the most cost-efficient approach.

Conclusions

This article describes the peculiarities of successive processes of quarry dumps that differ in age and climatic conditions. These are Kuznetsk coal basin (the Russian Federation), Sokolovsky quarry (Kazakhstan) and Inguletsky quarry (Ukraine). Research at these sites took place between the spring and summer of 2000–2020. The physical and chemical properties of the soil substrates studied at Kuzbass and the results of the mesomorphological studies showed relatively high conversion rates. In this area, organic matter accumulation in surface horizons increased with age and the pH decreased to 4.8. A similar trend was observed in earlier quarries – Inguletsky and Sokolovsky, although higher pH values were recorded.

The basal soil respiration rate at the Kuzbass quarry was extremely low (approximately 0.2 mg CO_2/g soil/h). The content of CO_2 in carbonate ranged from 0.05% to 0.6%, with the highest values observed in the territory of the older Kuzbass quarries rather than the younger quarries Inguletsky and Sokolovsky. Microbial biomass in Kuzbass soil ranged from 0.87 to 5.10 µg C/g soil, while in other quarries it was 6 times less. It is associated with these objects at an early age. The study of the diversity of floral species in the Kuznetsk coal basin identified 120 superior plant species from 34 families, among which cereals, legumes and representatives of mosses, lichens and algae dominated. In the territory of Inguletsky and Sokolovsky quarries, variety of species of plants was much poorer.

Scientific studies have shown that an important part of careers can be successfully restored through self-management. We also recommend the preservation of the complex terrain of the quarry, which will have a positive impact on the level of biodiversity. Our data demonstrate that remediation is required for sites with many ecological constraints, which is the practical value of the work performed. An important opportunity to increase the rate of succession and maintain ecosystem stability is to increase the proportion of microorganisms belonging to oligotrophs in the early stages of overgrowth, which is planned for investigation in the future work. Another focus of future research will be to investigate the possibility of speeding up the restoration of flora in the landfills of younger quarries through the formation of mycorrhizal communities.

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