Original article

Restoration of vegetation around mining enterprises

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A B S T R A C T

This paper is devoted to the restoration of vegetation around mining areas on the example of two land-reclamation zones in the Borodinsky coal mine during spring-summer of 2011–2021. Analysis of vegetation in this area has shown that indicators of spontaneous plant diversity in plots No. 1 and No. 2 were considered moderate in both layers (H < 2.5). Underwood and seeding diversity indices at pre-mining sites were ranked high, reaching 4.01–4.25 and 3.78–3.82, respectively. The analysis of the biological diversity of the flora in the undergrowth of the 12-year-old plot revealed approximately 29 spontaneous plant species belonging to 25 genera and 18 families. The most significant number of species found was found from the family Euphorbia, Cereals, and Legumes. At the 18-year-old site, the number and diversity of plant species (38 species) belonging to 38 genera and 27 families are slightly larger, with the most significant number of species within Euphorbiaceae and Poaceae, Asteraceae, Rubiaceae and Leguminosae. Saplings of various tree species from the Euphorbia and Leguminous family, such as *Euphorbia cyparissias* L., *E. fischeriana* Steud., *Desmodium triflorum* L., *Indigofera gerardiana* (Wall.) Baker, *Robinia viscosa* Vent. grew well in both plots. Many other spontaneous species of trees were also found in small populations at the 18-year-old site, namely, Pinus sylvestris L., *Salix alba* L., *Populus alba* L., and *P. tremula* L. In contrast to the younger site, some seedlings of small trees like *S. alba* and *P. tremula* and terrestrial ferns such as common bracken (*Pteridium aquilinum* (L.) Kuhn) and *adiantum capillus-veneris* L. prevailed in the older site.

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1. Introduction

In most countries, open pit mining, commonly used in commercial coal mining, remains a rather acute issue. This resulted in irreversible degradation and a complete change in the ecological system. The natural landscape has been disrupted and damaged, including the destruction of biodiversity in ecosystems by eliminating natural soils, plants, animals, and microorganisms (Hunter, 2007). Since coal is extracted at least shortly after work stops, a decision must be taken on how the site will be rehabilitated with all mine waste. Remediation of the site following mining is essential and becomes the responsibility of all mine operations. Mine landfill rehabilitation should be as similar as possible to earlier natural forms. However, quarry breeds have challenging conditions for the rooting and growth of plants because of their low organic matter content, heavy metal content, and other adverse physico-chemical features (Tangahu et al., 2011). Nitrogen-fixing legumes are recognized as crucial components in natural succession. These species are critical since the associated rhizobial symbioses are a source of nitrogen in the ecosystem (Requena et al., 2001). All affected woody legumes are also symbiotic with mycorrhizal fungi (Zhang et al., 2016). Fungal mycelium, which stretches from mycorrhizal roots, forms a three-dimensional network that connects the roots with the soil environment. It is an effective system for absorbing nutrients (particularly phosphorus) and eliminating them under low-nutrient conditions. Mycelium also promotes the formation of water-resistant aggregations required for good tillage (Rillig and Mummey, 2006).

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Peer review under responsibility of King Saud University.

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Plant succession following external disturbance associated with open-pit mining has ecological and practical interests (Wu et al., 2019). During plant rooting at different stages of succession, the recolonisation of varying plant species plays an essential role in the soil-forming process, promoting vegetation succession by improving soil conditions. The effectiveness of ecosystem restoration can be assessed in terms of the rate of natural or spontaneous restoration of vegetation and the status of nutrients in soils. To some extent, fertilizers meet plant nutrient needs (Bindraban et al., 2015). However, fertilizers (mainly applied in the long term) can cause environmental problems and damage ecosystems, such as groundwater pollution, greenhouse gas emissions, changes in soil physicochemical properties, and implication of soil food chains (Savci, 2012). Concerning these issues, the introduction of legumes into quarries is considered a sustainable land use practice. Due to their ability to fix nitrogen, many legumes are cultivated to improve soil fertility. In addition, they are commonly used to enhance net primary productivity, including grain, timber, and forage yields, in anthropogenic ecosystems. (Gao et al., 2017). The presence of legumes has also been reported to increase soil carbon sequestration (Wu et al., 2016). In addition, deposition from nitrogen-rich legume crops is more readily degraded by soil microorganisms, and this effect can reach high trophic levels through bottom-up control (Savci, 2012).

To restore the resiliency of a disturbed ecosystem, it is important to address as many aspects of spontaneous vegetation as possible (Prach et al., 2001; McDonald et al., 2016). Consequently, there is a need to periodically study and monitor the diversity of spontaneous recolonization of plants in reclamation areas and how they survive.

Invasive alien species are currently identified as the primary threat to global biodiversity, ecosystem functions, economy, and human health (Shackleton et al., 2018). This is an increasingly serious management issue in parks and reserves, and it often complicates restoration and rehabilitation projects (Zhang et al., 2018). In the past, and to some extent now, foreign plant species have been used for land rehabilitation, land stabilization, and rapid development of the plant community (Gann et al., 2019). However, due to their toxicity and habitat characteristics, invasive alien species often emerge spontaneously and invade landscapes severely disrupted by mining, making it difficult to restore natural plants (Celesti-Grapow and Ricotta, 2021). As such, awareness raising and appropriate management of spontaneous emergence and expansion of invasive plant communities should be encouraged.

A successful rehabilitation program aims to accelerate the spontaneous restoration of fertility in rehabilitated soils and increase biodiversity. Comparative studies of spontaneous plant succession in disturbed areas provide crucial information on vegetation dynamics to ensure the success of a future reclamation program (Zou et al., 2019). However, information on the process of spontaneous plant succession in post-coal reclamation areas remains limited. This study compared spontaneous recolonization of plants in areas recovered after coal mining with two different ages of recolonization in the Borodinsky coal mine (Russian Federation). The stages of this study consisted of: assessing and comparing the diversity and variations in the composition of spontaneous recolonization of plants in reclamation areas after coal mining with two different ages of recolonization (12 and 18 years of age); determining the spontaneous invasion of alien plant species; analyzing main factors and their relationship with spontaneous plant recolonization; evaluating progress and effectiveness of succession in the reclamation process of both sites. The results of this study may provide baseline and technical benchmarks for coal mine management for a successful reclamation program for mining regions.

Considering the presence of an environmental gradient associated with the continental climate, the preservation of the landscape, and the high heterogeneity of regeneration treatments, this work aimed to study plant community restoration processes in the Borodinsky coal mine area, which is the novelty of the work.

Achieving this objective involved the following tasks:

- selecting improved areas of the Borodino section, differing in topographic characteristics and age, to study the succession characteristics of the floristic cover;
- identifying indices of spontaneous plant diversity in the study area;
- analyzing the variety of floristic species and the evolution of plant communities in two different age zones of the Borodinsky coal mine.

2. Methods and materials

2.1. Study region

The studies were completed during the 2011–2021 spring-summer season. on the territory of the Borodino coal strip mine (55°52′N 94°55′E) (Krasnoyarsk Territory), which was founded in 1950 and is one of the largest open-pit mines in Russian Federation (Fig. 1). This area has a moderately continental climate, characterized by relatively warm summers and moderately cold winters. The territory is predominantly forest-steppe and steppe. Moderately thick chernozems primarily represent soils.

A number of mining activities have formed a typical landscape in the region, long and deep recesses of the quarries are interspersed with long and high sandy rocks, gradually becoming flat sandy fields.

2.2. Sample selection

Since small-scale topographic differences strongly affect soil and vegetation succession (Kim and Kupfer, 2016), sites with different topographic characteristics and ages were selected: 1 – 12-year site, 2 – 18-year site (Fig. 1). An inventory of the quarry flora was made in the Borodinsky open pit area. Areas of 10 m have been created for each ecotype. Sampling sites were selected randomly to cover the most diverse range of topographic characteristics. The sampling depth was 30 cm (Williamson et al., 2002). All plant species, total projective coverage, and projective coverage for each species are identified at each site. Vegetative cover plants, shrubs and seedlings of trees less than 1.5 m high were considered undergrowth, while trees and small trees greater than 1.5 m high and less than 5 cm in diameter at breast height were considered seedlings. Furthermore, their plants (trees, shrubs, herbaceous plants and ferns) have been classified at each site (Kilinc et al., 2010).

2.3. Statistical analysis

Vegetation analytical data at all sites were compiled and calculated. When interpreting the data, a multivariate cluster analysis was performed to determine the model of variation in the composition of spontaneous plant species found in restoration areas. Obtained study results were processed using MANOVA multivariate analysis of variance in Microsoft Excel and Statistica 10 software package. The composition of spontaneous plant recolonization was estimated by analyzing Shannon-Wiener frequency, density, abundance, and diversity index (de Smith, 2018). Differences in the results obtained are significant at $P \leq 0.05$ according to Student's t-test.
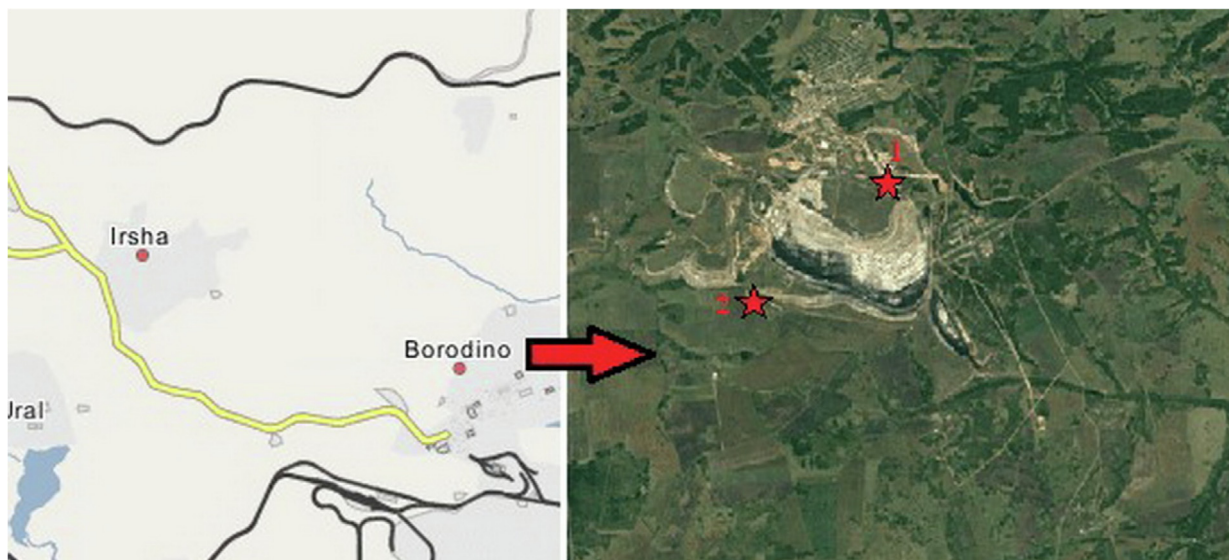
Fig. 1. Plots on the territory of the Borodinsky coal mine researched during 2011–2021 (1–12-year site, 2–18-year site).

3. Results

3.1. Plant diversity characterization

Vegetation restoration in the area of influence of mining companies was examined using the example of the Borodinsky coal mine in the spring-summer period of 2011–2021, where coal is still being extracted. For the study, 2 different land-reclamation areas were selected (Fig. 1) – the older and the younger, differing in topographic characteristics. Vegetation analysis of this area showed that spontaneous plants were recolonized in the two restoration plots at two levels, i.e., in the undergrowth and young seedlings. In contrast, the layers of trees were fairly sparse. In addition, indications of spontaneous plant diversity in both restoration areas were classified as moderate in both layers (H < 2.5). However, these diversity indices were found to be lower than the secondary forest near the sites prior to extraction. Undergrowth and seeding diversity indices at prime sites were rated high, reaching 4.01–4.25 and 3.78–3.82, respectively.

However, the number of plant species present in each layer of the former restoration plot was slightly more significant than that of the younger plot. This may be due to some plant species in the former reclamation site occurring in large populations, as indicated by the higher seeding density. As a result, in the two improved plots of this study, moderate spontaneous plant development and succession development were observed.

3.2. Composition and structure of plant communities

Various spontaneous plants were identified in both restoration areas. In the undergrowth layer of the 12-year-old plot, approximately 29 spontaneous plant species from 25 genera and 18 families were registered. The greatest number of species found were in the Euphorbia family, followed by cereals and pulses. In contrast, there was a slightly greater number and greater diversity of plant species (38 species) on the 18-year-old plot. They belonged to 38 genera and 27 families, with the largest number of Euphorbiaceae and Cereals species, followed by Asteraceae, Rubiaceae, and Leguminosae (Fig. 2).

According to plant habits categorization, the lower layer in both plots consisted mainly of shrubs and small trees, followed by tree seedlings, grasses, ferns, and herbaceous plants (Table 1).
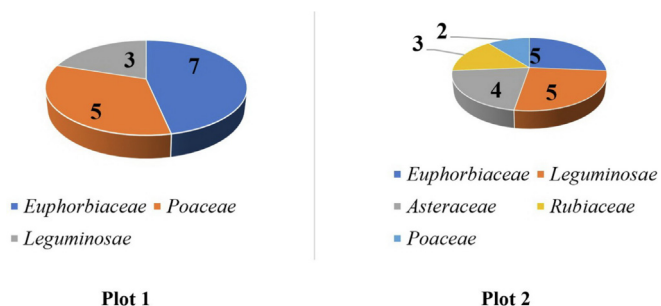

Fig. 2. The dominant complex of identified herbaceous plant communities on the territory of the Borodinsky coal mine in the spring-summer period of 2011–2021.

Table 1
The dominant complex of identified shrub and tree-like plant communities on the territory of the Borodinsky coal mine in the spring-summer period 2011–2021.

Plant communities	Shrub vegetation	Tree forms
Families of dominant plant communities	Sunflower family (Asteraceae) Mallow family (Malvaceae) Melastomaceae	Spurge family (Euphorbiaceae) Willow family (Salicaceae) Pine family (Pinaceae)
	Acanthus family (Acanthaceae) Potato family (Solanaceae) Barberry family (Berberidaceae)	Beech family (Fagaceae) Pea family (Leguminosae) Mallow family (Malvaceae)

Some of the shrub species recorded include those from the families Asteraceae, Malvaceae, Melastomaceae, Acanthaceae, and Solanaceae. Saplings of various tree species from the Euphorbiaceae and Leguminosae family, such as *Euphorbia cyparissias* L., *E. fischeriana* Steud., *Desmodium triflorum* L., *Indigofera gerardiana* (Wall.) Baker, *Robinia viscosa* Vent., known as common spontaneous pioneer plants on disturbed plots, grew well in both plots. *Cercis siliquastrum* L. and *Lespedeza thunbergii* (DC.) Nakai was considered spontaneous seedlings of pioneer trees planted for initial reclamation. Several other spontaneous tree species have also been

found in small populations at the 18-year-old site, namely *Pinus sylvestris* L., *Salix alba* L., *Populus alba* L., and *P. tremula* L.

Meanwhile, based on the species dominance on the 12-year-old plot, grass species like common meliot (*Melilotus officinalis* (L.) Desr.) prevailed. In contrast, shrub species of common barberry (*Berberis vulgaris* L.) prevailed on the 18-year plot (Fig. 3).

In this study, spontaneous competition from plant species at each site was reported. In general, grasses are less dominant in the older plot due to the lower intensity of light penetrating the shade of the undergrowth of the large pioneer trees compared to the younger plot. Shrub species such as *B. vulgaris* and bird cherry (*Prunus padus* L.) dominated in both plots. However, their species value was considered higher in the younger plot. In contrast to the younger site, some seedlings of small trees, including *S. alba* and *P. tremula*, and terrestrial ferns such as common bracken (*Pteridium aquilinum* (L.) Kuhn) and maidenhair fern (*capillus-veneris* L.) prevailed in the older site.

4. Discussion

The selection and management of pioneers to clean up degraded land is very important and becomes one of the keys to successful sanitation (Yu et al., 2020). Legumes on the territory of the Borodinsky coal mine (Fig. 2) were registred as pioneer plants that can quickly grow and adapt to poor soil conditions with a lack of nutrients. That effectively increases infiltration of the upper soil layer, reduces runoff and a risk of landslides (Chalise et al., 2019). They can also improve the soil and microclimate, degraded leaves act as green manures, the canopy provides full shade for the undergrowth and helps to retain air moisture around the plants. (Gao et al., 2017). Legume roots can also form symbiotic relationships between nitrogen and many strains of nitrogen-fixing microbes, which provide mineral nitrogen in soils for adjacent plants (Mus et al., 2016). Pioneer species should also first have high population growth rates and then decline when they are replaced by late-successive species (Marcante et al., 2009). This study found that pioneer legumes have low to medium longevity, so they will disappear over time and replace native tree species. A decrease in the number of large pioneer trees has already been found in both sites. However, the number is even higher in the old site than in the younger one.

Complex vertical stratification above and below the ground is characteristic of most natural forest ecosystems with closed forest cover. Restoration of this condition following resource extraction is a fundamental task of rehabilitation and reforestation (Pietrzykowski, 2019). The possible plant community developing on reclaimed mine lands will depend on landform and topography, local climatic and weather conditions, soil properties, vegetation restoration techniques, subsequent disturbance, impacts on wildlife, and land management methods (Fischer et al., 2014). The restoration of an enclosed undergrowth of native tree species may create a diverse community of native shrub plants (Bremer and Farley, 2010).

Moreover, revegetation is essential to facilitate soil development and promote the recolonization of native vertebrates and invertebrate fauna, creating conditions for vegetation rooting (Rey Benayas and Bullock, 2015). Strategically managed components are linked by species dispersal processes. Thus, ecological restoration at sites can support industrial practices and facilitate the return of wildlife in circumstances where social and ecological dynamics favour abandonment. When selecting species for reclamation, it is important to consider the site specifics, including moisture content, soil structure and fertility, salinity and pH, and availability of nutrients (Fischer et al., 2014). Moisture content in the soil is significant for the development of vegetation. Soil on the upper slopes often have very low soil moisture even in humid climates, requiring drought-tolerant species (Sardans and Peñuelas, 2013), such as *Pinus sylvestris* L., *Salix alba* L., *Populus alba* L., and *P. tremula* L. Excess soil moisture can also occur in mine rehabilitation zones. It often occurs in seeps on the lower half of the slopes or on the surface of areas where the soil is highly compacted, where water cannot enter the soil (Nguemezi et al., 2020).

The chemical properties of the soil will interfere with successful vegetation restoration. Liming and fertilizing the soil can make mine soils more suitable for vegetation in limited conditions (Fischer et al., 2014), although fertilization can increase cover and the number of exotic species (Talento et al., 2020). Mine soils with a high content of heavy metals can be cultivated to reduce their bioavailability, and metal-tolerant plant species can restore vegetation in such areas. However, it is important to consider whether these metals accumulate in the surface (Tangahu et al., 2011). Similarly, salt or sodium may be treated, but it may also require salt-tolerant species available from natural saline sites in the mining region (Shrivastava and Kumar, 2015). Suppose the pH of the reclamation area differs from that of the surrounding area. In that case, it will be essential to actively create vegetation in this area since there may not be suitable species available for colonization, and natural succession will be slow (Hagen and Evju, 2013).

Fig. 3. Dominant plant species in the studied areas of the Borodinsky coal mine.

The nature of the cover material has a major influence on the physical and chemical properties of the developing soil, which in turn affects the successful restoration of vegetation. This is particularly evident in the example of the recovery of coalfields (González-Martínez et al., 2019). Such a material can be common bracken and maidenhair fern, identified at a younger site of the Borodinsky coal mine.

The processes for restoring plant communities in quarries with different substrates have been sufficiently studied. Most studies address different aspects of vegetation succession (Garófano-Gómez et al., 2017; Hong et al., 2019). The soil formation processes have been analyzed in sufficient detail (Egli et al., 2018). However, few exhaustive observations of land and vegetation cover restoration and the relationship between these components. Regarding the vegetation of the studied Borodino section, the presented data prove that the increase in the number of mycorrhizal plants (in particular legumes), regularly observed during natural successional processes, is effectively repeated with a rather rapid primary succession in unfavorable habitats of the technogenic dump (Krüger et al., 2017).

5. Conclusions

This document describes the findings of the study of vegetation restoration processes in the area of influence of mining companies on the example of two reclamation areas of the Borodinsky coal mine in the spring-summer period of 2011–2021. Vegetation analysis of this area showed that spontaneous plants were recolonized in both reclamation plots in two tiers, that is, in the undergrowth and young seedlings; while the layers of trees were quite sparse. Additionally, indices of spontaneous plant diversity in regeneration plots No. 1 and No. 2 were classified as moderate in both layers (H < 2.5). However, these diversity indices were found to be lower than the secondary forest near the sites prior to extraction. Undergrowth and pre-mining site planting diversity indices were high, reaching 4.01–4.25 and 3.78–3.82, respectively. The analysis of the biological diversity of the flora in the undergrowth of the 12-year-old plot showed approximately 29 spontaneous plant species belonging to 25 genera and 18 families. The largest number of species were found in the family Euphorbiaceae, Poaceae, and Leguminosae. While there was a slightly greater number and greater diversity of plant species (38 species) belonging to 38 genera and 27 families on the 18-year-old site. The largest number of species were recorded in Euphorbiaceae and Poaceae, Asteraceae, Rubiaceae and Leguminosae. Saplings of various tree species from the Euphorbia and Leguminous family, such as *Euphorbia cyparissias* L., *E. fischeriana* Steud., *Desmodium triflorum* L., *Indigofera gerardiana* (Wall.) Baker, *Robinia viscosa* Vent., known as common spontaneous pioneer plants on disturbed plots, grew well in both plots. *Cercis siliquastrum* L. and *Lespedeza thunbergii* (DC.) Nakai were considered spontaneous seedlings of pioneer trees planted for initial reclamation. Several other spontaneous tree species have also been found in small populations at the 18-year-old site, namely *Pinus sylvestris* L., *Salix alba* L., *Populus alba* L., and *P. tremula* L. It has been scientifically proven that the reclamation part of the Borodino section tends to successful self-restoration. It is also recommended to conserve the challenging terrain of the quarry, which will positively affect the level of biodiversity. The data from this research show that remedial measures are needed for areas with many ecological restrictions, which is the practical value of the research conducted.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be available on request.

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