Post-Mining Restoration in South-Central British Columbia: Modelling Microbial and Geochemical Changes in Topsoil Stockpiles (NTS 092I/09, 093A/12)

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Introduction

The mining industry in Canada is an essential source of resources and a key contributor to the economy. In 2018, mining contributed $69.5 billion dollars to real GDP and provided approximately 626 000 jobs. In British Columbia, the gross mining revenue amounted to 12.3 billion in 2018 (Mining Association of British Columbia, 2019). Federal and provincial regulations ensure that the restoration or reclamation of landscapes is conducted at minesites to repair disturbances and return the land to a sustainable ecosystem with a historical level of productivity. Research to understand and optimize restoration practices is crucial because needs and response vary greatly from site to site and from ecosystem to ecosystem. Mining is particularly damaging to ecosystems because soils are stripped from landscapes and require reconstruction, which would take hundreds or thousands of years if left to natural processes (Bradshaw, 1997).

To preserve valuable topsoil in mining operations, it is common practice to store stripped topsoil on site as a topsoil stockpile for ecosystem rehabilitation. Stockpiled topsoil can be used post mining to provide nutrients, structure and seeds, and to amend waste materials on site. However, it is known that microbial composition and functions degrade significantly over time, likely depending on factors such as stockpile depth, exposure to sun, weather, temperature, and chemical and microbial interactions (Abdul-Kareem and McRae, 1984; Stahl et al., 2002; Ghose and Kundu, 2004). Stockpiles are highly variable between sites, can reach up to 30 m in height and may sit for the entire duration of mine operation, which could be decades. In addition to possible negative impacts from stockpile height and age, the proper segregation of topsoil from the underlying subsoil is often not possible, resulting in dilution of the topsoil.

The inability to preserve topsoil is one of the basic hindrances to restoration of mining operations. A major question is, "do long-term large topsoil stockpiles remain viable?" In order to address this question, characterization of topsoil-stockpile viability must be carried out by sampling profiles of large stockpiles, and strategies must be developed to increase the viability of stored stockpiles.

Despite the rising demand for restoration management, there is limited research on environmental restoration and there are few dedicated university postgraduate training programs in Canada to address the complexities of ecosystem reclamation. There is a critical need to work with the mining and oil-and-gas industries, in partnership with government agencies, to develop better management practices for successful ecosystem restoration.

Research Objectives

This project investigates factors that affect changes to soil health in topsoil stored in stockpiles by evaluating the stockpiles at two gold operations in BC (Figure 1) The aim is to model changes in factors affecting soil health and function with depth, including geochemical properties and microbial communities. By characterizing these stockpile profiles, the study will improve understanding of the impacts of severe disturbance on soil properties and ecology, and highlight the role of bacteria and fungi in restoration.

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The working hypothesis is that the topsoil-stockpiling practices at the New Afton mine (Figure 2) and QR mill (Figure 3) have had adverse effects on soil properties. Consequently, it is predicted that there will be significant differences in soil composition between depths within the topsoil stockpiles.

Methods

Study Sites and Soil Sampling

New Afton Mine (New Gold Inc.)

The New Afton copper-gold mine of New Gold Inc. is located approximately 10 km west of Kamloops in BC's southern interior. It comprises underground workings, historical support facilities, a historical open pit, a concentrator and a tailings facility. The end land-use objective is to return the ecosystem to native grasslands that support wildlife and traditional hunting opportunities for First Nations (New Gold Inc., 2018). New Afton is located within the traditional territories of the Tk'emlúps te Secwépemc and Skeetchestn bands. These bands are part of the larger cultural group known as the Secwépemc or Shuswap First Nation. Additionally, New Afton is in the Bunchgrass (BGxw1) biogeoclimatic zone at 330–1000 m in elevation. The BGxw1 is commonly known as the 'middle grasslands' and is dominated by bluebunch wheatgrass, junegrass, big sagebrush and rabbit brush (Lloyd et al., 1990).

Figure 1. Sample sites at the New Afton mine (New Gold Inc.) and QR Mill (Barkerville Gold Mines Ltd.), located in British Columbia's southern interior. Map generated in QGIS® with Bing VirtualEarth background.

New Afton has a 7-year-old topsoil stockpile that is 25 m deep and contains approximately 250 600 m^3 of topsoil materials. The removal and stockpiling process resulted in some mixing of A, B and C horizons. Sampling of the topsoil stockpile of interest occurred on September 26 and 27 of 2018. Four soil cores were extracted via solid stem auger drilling by Geotech Drilling Services Ltd., the drillholes being approximately 3 m apart. The stockpile was sampled

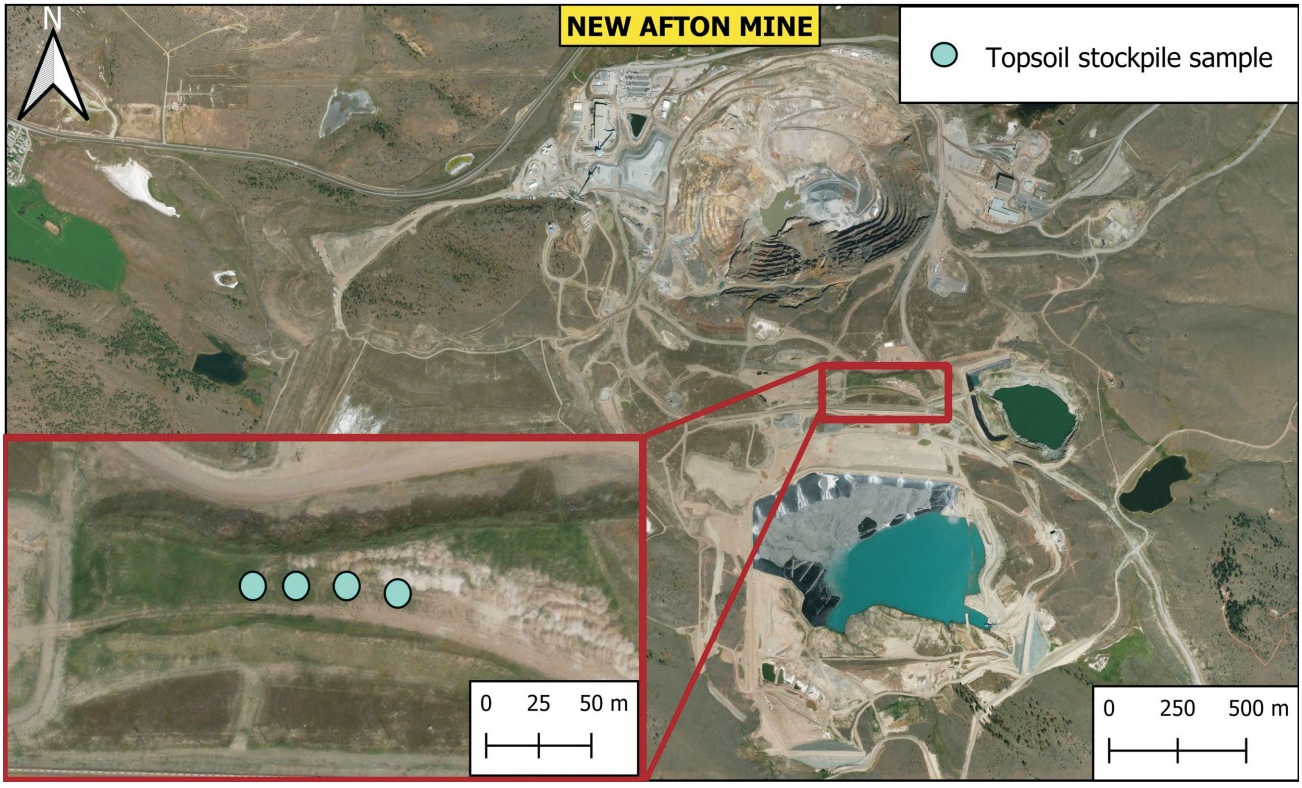

Figure 2. Aerial image of the New Afton minesite, including a close-up of the topsoil stockpile of interest that shows the locations of soil samples. Map generated in QGIS® with Bing VirtualEarth background.

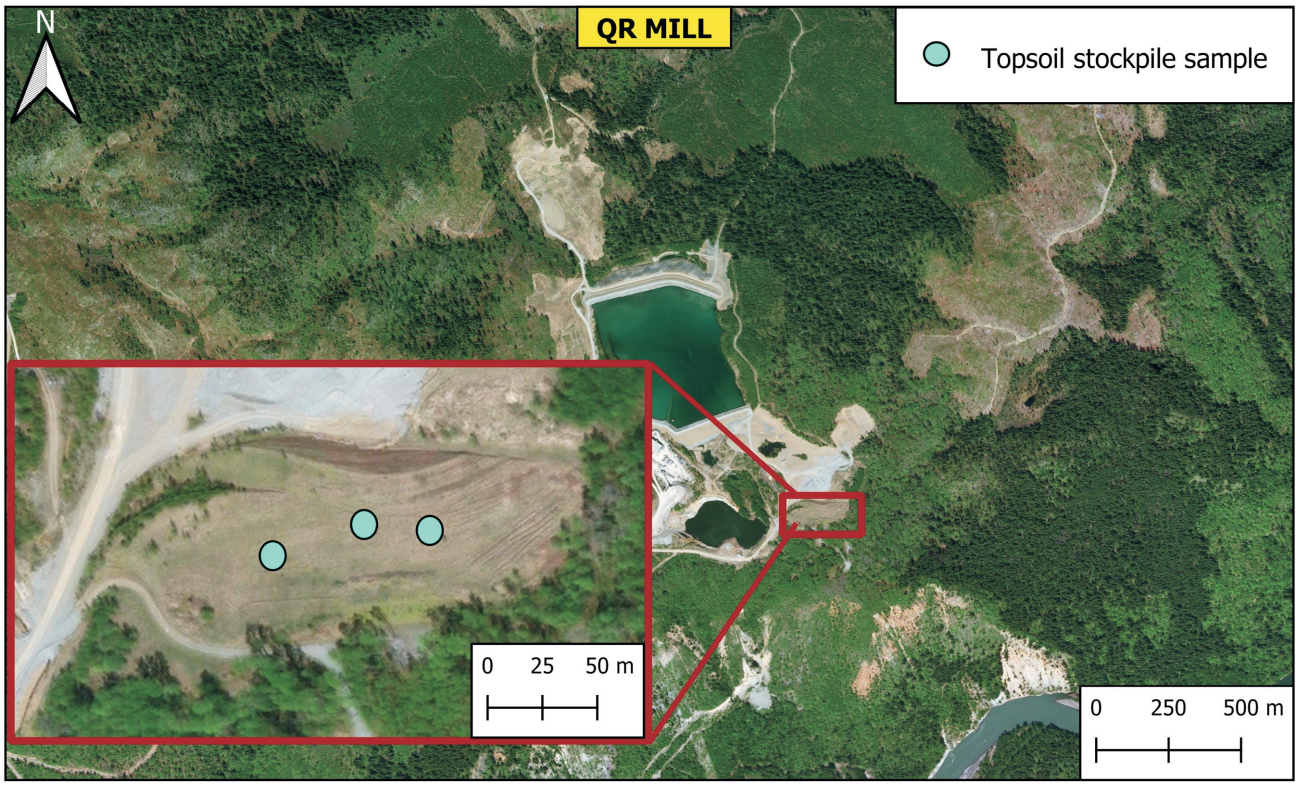

Figure 3. Aerial image of the QR mill, including a close-up of the topsoil stockpile of interest that shows the locations of soil samples. Map generated in QGIS® with Bing VirtualEarth background.

in 0.3 m intervals until the bottom of the stockpile was reached at 13.7 m. The outer 1 cm of the soil core was discarded from each sample to ensure that collected soil was not contaminated by upper layers. Soil samples were originally collected from the thirteen different intervals and then combined into four intervals (0.0–0.6 m, 0.6–1.5 m, 1.5–6.1 m and 6.1–13.7 m) for testing. The interval size increased with depth because the most activity and differences with depth were expected closer to the surface of the pile. A reference soil sample of approximately 16 kg was collected from the top 10 cm at a nearby grassland site.

QR Mill (Barkerville Gold Mines Ltd.)

The Quesnel River (QR) mill of Barkerville Gold Mines Ltd. is located approximately 80 km east of the city of Quesnel in the Cariboo district of BC's southern interior. Ore and concentrate from the Bonanza Ledge mine and Cariboo Gold mine are transported and processed in the QR mill. The mill is also used as a tailings-storage facility. It is situated in the traditional territories of the Secwépemc or Shuswap First Nation and lies within the Engelmann Spruce–Subalpine Fir (ESSF) biogeoclimatic zone at 1200–1500 m elevation. The ESSF is the wettest zone of the Cariboo Forest Region (mean annual precipitation 1044 mm) and is dominated by oak fern, foamflower, rose twisted-stalk, feathermosses, Engelmann spruce and subalpine fir. The current reclamation goal set for the QR mill is to restore the landscape so that it does not require further human intervention (Barkerville Gold Mines Ltd, 2019).

The QR mill has a 20-year-old topsoil stockpile that is 6 m deep. It is a combination of organic soil and general till soil stripped from the surface. The stockpile is intended to be respread during post-mining reclamation. Sampling at the QR mill was completed in May 2019. Three holes, approximately 100 m apart, were dug using an excavator to access various layers of the stockpile: 0–10 cm, 10–20 cm, 60–120 cm, 200–260 cm, 350–390 cm and 500–575 cm. A corresponding reference soil sample was collected from the top 10 cm in an undisturbed forest site adjacent to the mill.

Experiment Design

The variation of all measured soil properties with depth was summarized using principal component analysis (PCA) on scaled geochemical variables (ggfortify in R). To test for significant differences in centroids between different depths, permutational multivariate analysis of variance (PERMANOVA) was measured using the adonis function from the vegan package in R. All errors are reported as standard error. To visualize differences in bacterial and fungal communities between stockpile depths, a non-metric multidimensional scaling (NMDS) plot was calculated for each sample site.

Characterizing Soil Geochemical Properties

The major-element composition of the soil samples is being measured at the analytical laboratory of the Ministry of Environment and Climate Change Strategy in Victoria, BC. The samples were prepared by heating soil samples at 70°C for 24 hours, followed by sieving through a 2 mm pan. The report will include a complete profile of all major elements; Al, B, Ca, Cu, Fe, Mg, Mn, P, K, S and Zn by acid and microwave digestion; available P by Bray P-1 extraction and UV analysis; and available NH_4^+ and NO_3^- by KCl extraction.

In the Thompson Rivers University (TRU) greenhouse lab, organic matter and moisture content were measured using loss-on-ignition (LOI), and pH and electrical conductivity (EC) were determined using a Palintest® 800 meter. The loss-on-ignition was calculated by weighing approximately 1.5 g from each sample of soil into a tin and then heating it at 105°C for 12 hours and then 500°C for 5 hours. The dried soil was weighed to calculate its water content and organic content.

Lastly, total C, S and N were measured with a Thermo-Scientific CHNS Elemental Analyzer. These samples were prepared for analysis by drying in an oven at 70°C for 24 hours, followed by sieving through a 2 mm pan and grinding with a mortar and pestle in the greenhouse lab.

Metabarcoding Soil Microbial Communities

The microbial-community composition of soil samples was characterized in the Applied Genomics Laboratory at TRU (TRUGen, Rockville, Maryland). The DNA from the soil samples was extracted using a MagAttract PowerSoil DNA Kit (QIAGEN, Hilden, Germany) and a portion of the bacterial 16S rRNA gene was amplified by Polymerase Chain Reaction (PCR) using primers 341F and 806R. For fungi, the primers ITS86F and ITS4R were used to amplify the second internal transcribed spacer of the nuclear ribosomal DNA (ITS2) region between the 5.86S rRNA and 28S rRNA genes. Amplicon libraries were prepared for sequencing during a second round of PCR with indexed primers, and purified with AgenCourt AMPure (Beckman Coulter Inc., Brea, California) magnetic beads to remove DNA under 100 base pairs in length. Sequencing was carried out using 400 base-pair chemistry on an Ion Torrent S5 XL platform (Thermo Fisher Scientific, Waltham, Massachusetts). Filtered sequencing reads were rarefied as outlined in McKnight et al. (2019). Operational taxonomic units (OTU) clustering and taxonomy assignment were carried out using the bioinformatic pipeline AMPtk (Palmer et al., 2018).

Preliminary Results

Changes in Geochemical Properties with Stockpile Depth

Principal component analysis (PCA) suggests that changes with depth led to changes in soil properties. The first principal component (PC1) explains 41.09% of variation and the second principal component (PC2) explains 18.47% of variation seen between samples (Figure 4). Running PERMANOVA on the New Afton ($p = 0.022$, $R^2 = 0.29$) and QR mill ($p = 0.038$, $R^2 = 0.27$) samples shows a significant difference in geochemical properties with stockpile depth (Figure 4). There is relatively little spread within the New Afton samples, but a relatively high amount of spread is observed in the QR mill samples. Here, the depths represent a rough gradient, with the top intervals being close together at the top right and the bottom depth intervals being the most distant. Additionally, the stockpile samples from both New Afton and QR mill are highly separated from their corresponding reference soil samples.

Changes in Soil Microbial Communities with Stockpile Depth

Preliminary non-metric multidimensional scaling (NMDS) plots illustrate that bacterial and fungal communities in reference soils are separated from their corresponding stockpile soils (Figure 5). Additionally, results indicate that there are significant differences in bacterial communities with depth in QR mill soil ($p = 0.001$, $R^2 = 0.55$) but not New Afton soil ($p = 0.08$, $R^2 = 0.19$). Furthermore, there are sig-

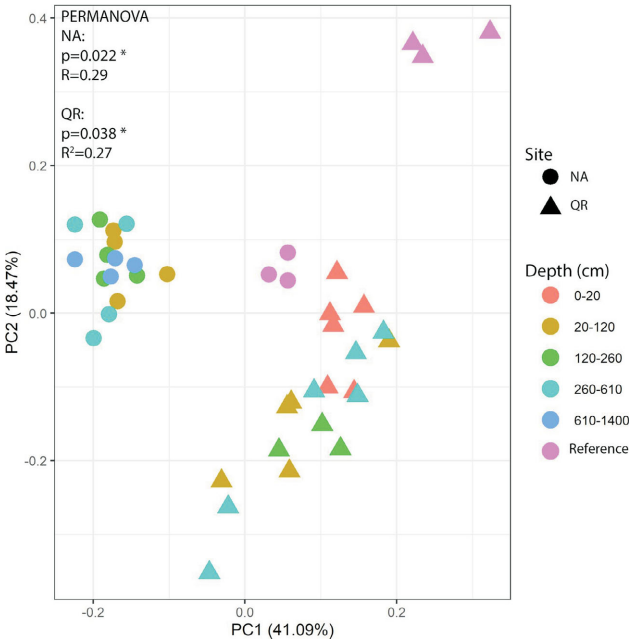

Figure 4. Principal component analysis (PCA) plots showing differences in soil chemical properties with changing stockpile depths at New Afton (NA) and QR mill (QR). Significance level represented by '*'.

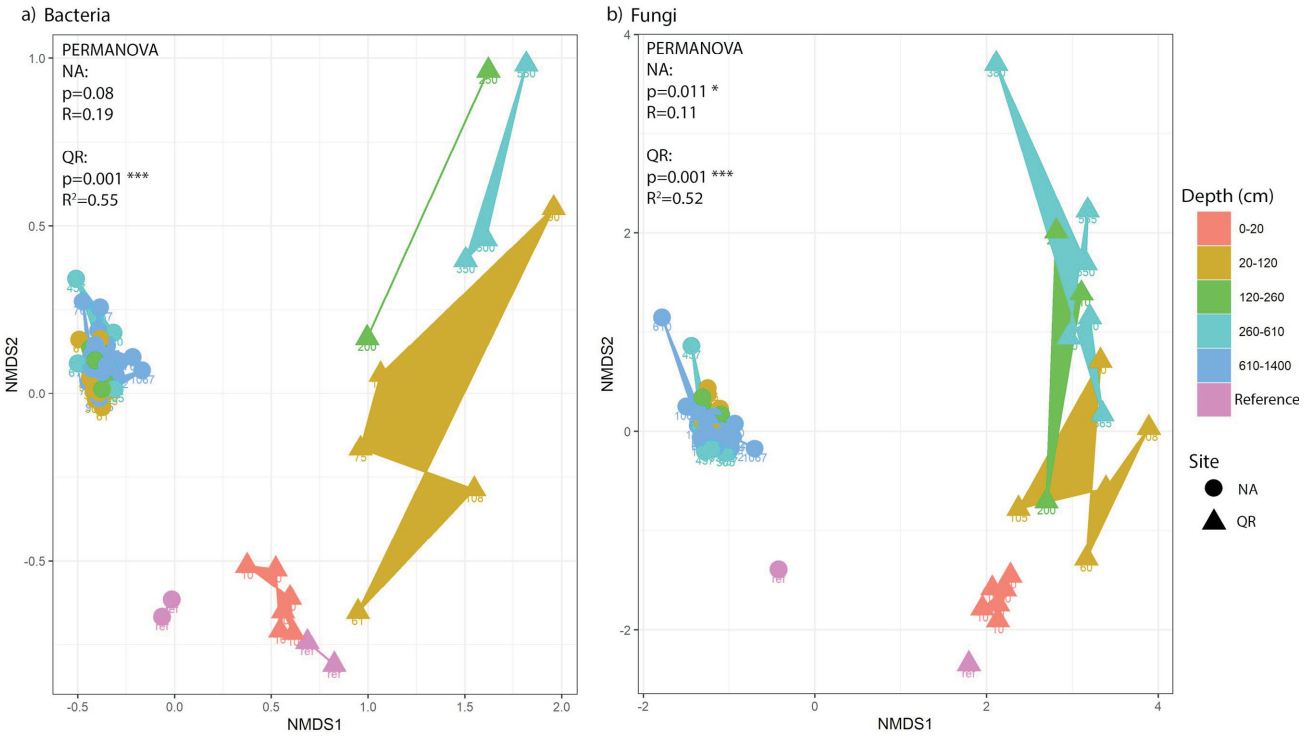

Figure 5. Non-metric multidimensional scaling (NMDS) plots showing differences in bacterial communities **(a)** and fungal communities **(b)** with changing depths in the New Afton (NA) and QR mill (QR) topsoil stockpiles. Significance level represented by '*'.

nificant differences in fungal communities with depth in the New Afton ($p = 0.011$, $R^2 = 0.11$) and QR mill stockpiles ($p = 0.001$, $R^2 = 0.52$). Bacterial and fungal communities are relatively less similar between depth intervals in the QR mill stockpile than in the New Afton stockpile. This pattern matches what is observed with the PCA of geochemical properties (Figure 4).

Discussion

These results are preliminary and therefore subject to modification as research continues. The vertical position within the topsoil stockpile impacts the geochemical and microbial characteristics of the soil profile. However, the changes with depth observed in the New Afton stockpile were relatively smaller than those observed in the QR mill stockpile (Figures 4, 5). Interestingly, bacterial communities changed significantly with depth in only the QR mill stockpile, whereas fungal communities changed significantly with depth in both the New Afton and QR mill stockpiles. The smaller changes with stockpile depth observed at New Afton compared to QR mill may be a product of various site-specific influences, such as the difference in stockpile age or the addition of fresh topsoil.

Additionally, these preliminary results indicate that the geochemical properties in reference soils are notably distinct from those of the corresponding stockpile soils. The NMDS ordination plots show that bacterial and fungal communities in the reference soils are also noticeably different than those in the corresponding stockpile soils. The bacterial and fungal communities found in the deepest soil interval (260–610 cm) of the stockpile are farthest from, and those in the top soil interval (0–20 cm) closest to, the reference soil samples at QR mill. This indicates that increasing stockpile height may drive communities in the deeper soils farther away from their historical state, creating a greater barrier to restoration. Not surprisingly, this shows that long-term storage of topsoil can cause significant chemical and microbial alteration. These findings are supported by a study by Harris et al. (1989), which found that when soil was stockpiled in piles that were more than a metre deep, chemical effects such as accumulation of ammonium and establishment of anaerobic conditions occurred in the topsoil at the base of the pile. Additionally, Mummey et al. (2002) showed that reapplying stockpiled topsoil to overburden materials post mining had long-lasting detrimental effects on plant diversity, soil microbial populations and soil organic-matter content compared to undisturbed sites, even 20 years after seeding of the reclaimed sites.

Conclusions

This project addresses knowledge gaps in the industry by exploring the compositional nature of topsoil stockpiles and their ability to facilitate post-mining revegetation. Specifically, these results highlight the important influence of topsoil-stockpile height on the geochemical properties and microbial communities in the soil, which ultimately influ-

ences the success of restoration. Optimized reclamation methods that allow for a more harmonious coexistence between industry and environment are needed. This need can be met, in part, by research focused on understanding and mastering ecosystem-reclamation processes.

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