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CIRAN

D2.2 Criteria for 'good practices' in systemic permitting

Guidelines for rehabilitation of extractive sites in environmentally protected areas

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Executive summary

The purpose of this report is to compile comprehensive guidelines and good practices for conducting rehabilitation activities on mine sites located in environmentally protected or sensitive natural areas, whether on an ongoing, progressive basis during operations or at End of Life of the mine. Based on the 15 case studies presented in CIRAN deliverable 2.1, these guidelines will pay particular attention to the importance of environmental rehabilitation from a social and economic point of view. Additionally, it explores the role of systemic permitting in facilitating effective rehabilitation processes, ensuring that regulatory frameworks support sustainable mining practices throughout the project lifecycle.

While mining plays a vital role in supplying essential raw materials for industry and infrastructure, with particular focus on the EU Green deal and the Critical Raw Materials Act, the damaged ecological footprint often in the past left by mining operations underscores the urgent need for adopting a working culture of deploying effective rehabilitation efforts during mining on an ongoing basis, not just doing them at the end.

A life-cycle management approach in the rehabilitation process is necessary. It's important to define an integrated project that begins at the mine planning stage, where closure and rehabilitation of the mine itself and any extractive waste management facilities are already envisaged.

The guidelines address some aspects related to the design of recovery interventions and their insertion in the environmental and social context, emphasising the fundamental role of local populations as key stakeholders from start to finish. The participation of local stakeholders in the design, implementation and monitoring phases of the recovery intervention is essential to delivering a socially and economically sustainable result, a goal whose success or failure may well have knock-on implications for other mines in the area or the whole country. Of equal importance in a circular economy will be the need for futureproofing a mine that may well have ceased operations for economic reasons such that its resources remain recoverable in future, when more favourable market conditions return.

The guidelines were shared with the CIRAN project experts at a meeting in Bologna on 30 September 2024.

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1 Introduction

1.1 Objective

The objective of this deliverable is to analyse the case studies presented in WP2, collected and summarized in deliverable 2.1 (Luodes et.al, 2024), from the perspective of best practices for the recovery and rehabilitation of mines. Using existing tools, a synthesis of the results will be carried out and guidelines will be drawn up to assist sponsors and practitioners in designing and delivering the optimum rehabilitation project for a specific area.

1.2 Framework

Mining has been a critical part of human civilization for centuries, providing essential resources for industry, infrastructure, and technology. However, the environmental impact of mining activities can be severe, often leading to habitat destruction, water pollution, and loss of biodiversity. In recent years, there has been a growing recognition of the need for ongoing mine rehabilitation efforts to mitigate these impacts and restore ecosystems to their original state or an equivalent condition on a continuous basis. Mine exploration is a cornerstone of sustainable resource development, driving economic growth, technological innovation, and environmental stewardship. By uncovering new mineral deposits, fostering scientific discovery, and promoting responsible practices, exploration efforts pave the way for the responsible extraction of mineral resources essential for modern society. As we navigate the challenges of resource scarcity, climate change, and global sustainability, the importance of mining exploration as a catalyst for positive change cannot be undervalued?

Mining rehabilitation, also known as mine reclamation or rehabilitation, is the process of restoring land and ecosystems that have been disturbed by mining activities. It represents a critical stage in the lifecycle of a mine, aiming to mitigate environmental impacts, restore ecosystems, and promote sustainable land use. While mining plays a vital role in supplying essential raw materials for industry and infrastructure, with particular focus on EU Green deal (EC, 2019), the damaging ecological footprint left by many mining operations in the past underscores the urgent need for effective rehabilitation efforts with increasing emphasis on continuous as well as end of life activities.

2 Context: overview of mining impacts on the environment and communities

Mining activities typically have significant impacts on the environment and local communities. But the nature of these impacts varies depending on the location, scale, and type of mining operations. They commonly include ecological degradation, water and air pollution and social and economic disruption.

2.1 Environmental impacts

An inventory of environmental impacts will likely include the following aspects:

Land Degradation and Habitat Loss: Mining involves the removal of earth to extract minerals, which significantly alters the landscape. This may lead to the degradation or even destruction of habitats for flora and fauna, decreases biodiversity, and disrupts ecosystems. Open-pit mining and mountaintop removal are particularly destructive as they change landforms by permanently altering the landscape.

Water Contamination: Mining processes often lead to water pollution through the discharge of toxic chemicals used in mineral processing and the leaching of pollutants from mine overburden and tailings, often misleadingly referred to in the industry as “wastes”. Loose use of the term “waste” has major regulatory consequences and of particular significance from a CE and CRM Act perspective may impede or even prohibit access to the valuable residual resources they may still contain (see reference to future-proofing). Acid mine drainage, where exposed minerals release acid into local waterways, is a common long-term problem that can continue to affect water sources long after a mine has closed. Other sources of pollution may result from the release of hydrocarbons and mineral oils into the soil from the fuels and lubricants, used by the vehicles and equipment operating in the mine.

Air Pollution: Mining operations emit particulate matter and gases including methane, sulphur dioxide, and volatile organic compounds. These emissions contribute to air pollution, which can cause respiratory problems in nearby populations and contribute to broader atmospheric issues like acid rain and global warming.

Soil Contamination: Heavy metals and other contaminants may deposit in soils through wind-blown dust particles that deposit around or close to mining sites, or they may leach out from tailings into the wider environment. This may lead to reduced soil fertility and can introduce toxins into the food chain, impacting wildlife and human populations alike.

Resource Depletion: Mining exhausts non-renewable resources, leading to potential shortages of critical minerals and metals. This depletion also often leads to increased costs and energy expenditure to access deeper or more remote deposits.

2.2 Social and economic impacts

An inventory of social and economic impacts will likely include the following aspects, typically classed as “negative externalities” meaning costs of various types imposed on communities without their consent:

Community Displacement and Social Disruption: Mining often requires the displacement of communities to make way for operations. This can lead to loss of livelihoods, changes in social structures, and cultural disintegration. It can also result in increased conflict, especially in regions where land rights are ambiguous or enforcement is weak.

Health Hazards: Communities near mining sites may suffer from health issues due to exposure to pollutants in air and water. Chronic conditions such as lung diseases from inhaling dust or heavy metal poisoning from contaminated water supplies are common.

Economic Dependency: While mining can contribute significantly to local economies through job creation and increased revenues, it can also lead to dependency. This is especially true in regions where mining is the dominant industry. When mines close, communities often face economic collapse unless diversification strategies are in place.

3 Importance of rehabilitation: benefits of restoring mining sites, including ecological, social, and economic aspects.

The rehabilitation of mining sites is critical to mitigating the adverse effects of mining operations and ensuring that areas previously used for mining and still containing potentially valuable resources can remain accessible for future use (Future-proofing}. Effective rehabilitation not only addresses environmental degradation but also fosters social stability and economic development. The rehabilitation of mining sites presents an opportunity to correct environmental wrongs while also offering a pathway to restore and enhance social and economic conditions. Investing in comprehensive rehabilitation practices is not just a regulatory requirement but a crucial step towards sustainable development. This holistic approach not only helps in healing the land but also in fostering a positive legacy for future generations.

Successful site rehabilitation can lead to situations in which final conditions may even be better than at the beginning, especially in the case of sites already impacted from an ecosystem point of view. The final recovery, depending on the chosen modality, may lead to a recovery of value from an ecological point of view, or from the point of view of the site's usability, or from both points of view.

3.1 Ecological benefits

An inventory of potential ecological benefits will likely include the following aspects:

Rehabilitation of ecosystems: rehabilitation involves restoring the vegetation and rebuilding the soil structure and fertility, which helps in bringing back local flora and fauna. This re-establishment of plant life supports biodiversity and helps in restoring ecological balance.

Improvement in water quality: properly managed rehabilitation can reduce the pollution load in local water bodies by stabilizing soil and reducing sediment run-off. Techniques like constructing wetlands can further treat contaminated water naturally, through phyto-purification.

Carbon sequestration: replanting trees and other vegetation helps in capturing atmospheric carbon dioxide, contributing to climate change mitigation. Restored forests and wetlands are important carbon sinks, which play a crucial role in global carbon cycling.

Soil stabilisation: rehabilitation helps in stabilizing the soil, reducing erosion risks, and preventing landslides and dust storms, which can have wider environmental impacts.

3.2 Societal benefits

An inventory of potential social benefits will likely include the following aspects:

Improved quality of life for local communities: effective rehabilitation can lead to cleaner air and water, which directly improves the health and well-being of nearby communities. It also helps in preserving local cultures and traditions by maintaining the landscapes that support them.

Creation of recreational spaces: many rehabilitated mines are converted into public parks, lakes, and other recreational facilities, providing community spaces that enhance the quality of life and promote social cohesion.

Educational opportunities: rehabilitated sites can serve as outdoor learning environments where schools and universities can study ecology, geology, and environmental science in a real-world context.

3.3 Economic benefits

An inventory of potential economic benefits will likely include the following aspects:

Recovery in property values: rehabilitation of mining areas often leads to a recovery in property values as the environmental conditions and aesthetics of the area improve and environmental risks are mitigated.

Value-add Job creation: the process of rehabilitation itself can create value-add jobs, and well-planned rehabilitation can lead to sustainable economic activities such as eco-tourism, agriculture, or forestry, which can provide long-term employment opportunities.

Diversification of local economies: by converting degraded land into productive use, communities can reduce their economic dependency on mining. This diversification is crucial for resilience, particularly in regions where mining is a major but unsustainable economic activity.

Regulatory compliance and corporate social responsibility: meeting regulatory requirements can avoid legal penalties, and demonstrating a commitment to responsible environmental practices can enhance a company's reputation and relations with stakeholders, including investors, regulators, and the community.

4 CIRAN Case studies

4.1 Introduction

To develop a concise list of principles and actions to guide the designer or planner in the sustainable exploitation of a mine and its final recovery, we will use some good practices already applied in real cases listed in WP2.

The Case Studies synthetized in the deliverable 2.1 cover different lifecycle phases of the extractive activity (see Table 1). Each case has an impact on, or connection with, one or more environmentally sensitive or nature protection areas. These operational sites typically overlap with a national park or a similar category of protected area but may also be located in the buffer zone(s) between protected or sensitive sites.

Table 1 – CRM Case Studies by country location, protected site and lifecycle (from Luodes et all., 2024).

Case /typology/ mineral extracted	Country Location	Protected area implicated	Lifecycle phase
Mittersill / underground / tungsten	Salzburg, Austria	Adjacent to the National Park "Hohe Tauern"	Active
Sakatti / N.A. / Cu, Ni, PGE-group metals	Sodankylä, Finland	Natura 2000	Exploration
Rompas-Rajapalot / N.A. / gold, copper	Ylitornio/ Rovaniemi Finland	Natura 2000	Exploration/ opening
Emili/ Beauvoir Lithium Mining Project / Lithium (CRM)	France	Adjacent to Nature protected area, designated SAC	Exploration Planning & Design
Blackstairs Lithium / N.A. / lithium-bearing pegmatites and aplites	Wicklow/Carlow, Ireland	EU designation (SAC), National (natural heritage area)	Exploration
Monte Tondo / dual / gypsum	Emilia-Romagna, Italy	Natural Park – UNESCO heritage candidate	Active/ under new assessment
Nussir ASA / underground / copper, gold, silver	Hammerfest, Norway	Seiland National Park	Opening/active
Neves Corvo/underground / copper, zinc, and lead	South Portugal	Area covered by Birds Directive & Habitats Directive	Active
Serra Candeeiros region / dual / limestone	Leiria, Portugal	National Nature Park. Extraction of dimension stones and industrial	Active (≥380 quarries, 770ha)
Barruecopardo / open pit /tungsten	Castilla y Leon, Spain	Natura 2000	Reopening
N. Sweden regional case / N.A. / Polymetallic	Västerbotten/ Norbotten, Sweden	Permitting in and adjacent to protected areas	Exploration/ opening
Våmb quarry/open pit/ Limestone	Sweden	Adjacent to protected areas	Active
Hemerdon Tungsten / open pit / tungsten-tin	Devon, UK	Historic environment record designation	Reopening/ operational

Case /typology/ mineral extracted	Country Location	Protected area implicated	Lifecycle phase
Redmoor / underground / tin-tungsten	Cornwall, UK	UNESCO cultural heritage area	Reopening/ exploration
Alligator river / open pit / uranium.	Northern Territory, Australia	Kakadu National Park (World Heritage site RAMSAR Conv.)	Rehabilitation

4.2 Austria: Mittersill tungsten mine

Figure 1 – Mittersill tungsten mine: Main entrance of the mine (Research gate).

Remediation activities have been conducted over many years. The Eastern part of the mine, the open pit, in a previous lifecycle stage was closed, decommissioned, recultivated and reinstated as alpine pasture as prior to mining. But as a result of technological advances it is now economically and technically feasible to extract lower grade ores. This has given rise to new plans to reopen some of the area previously thought to be mined out.

A legacy tailings pond is located near the mine and reaches a depth of 25m; it has been covered with compost and is now vegetated.

When the mine is restarted, the newly produced tailings will be covered with compost as well and revegetated after mine closure. Mine closure (End-of-Life) procedures are planned to last 2-4 years after termination of mining activities.

While continuing to operate the underground mine in the Western zone, the voids have been filled and consolidated with tailing materials and binder.

4.3 Finland – Rompas-Rajapalot gold and copper mine

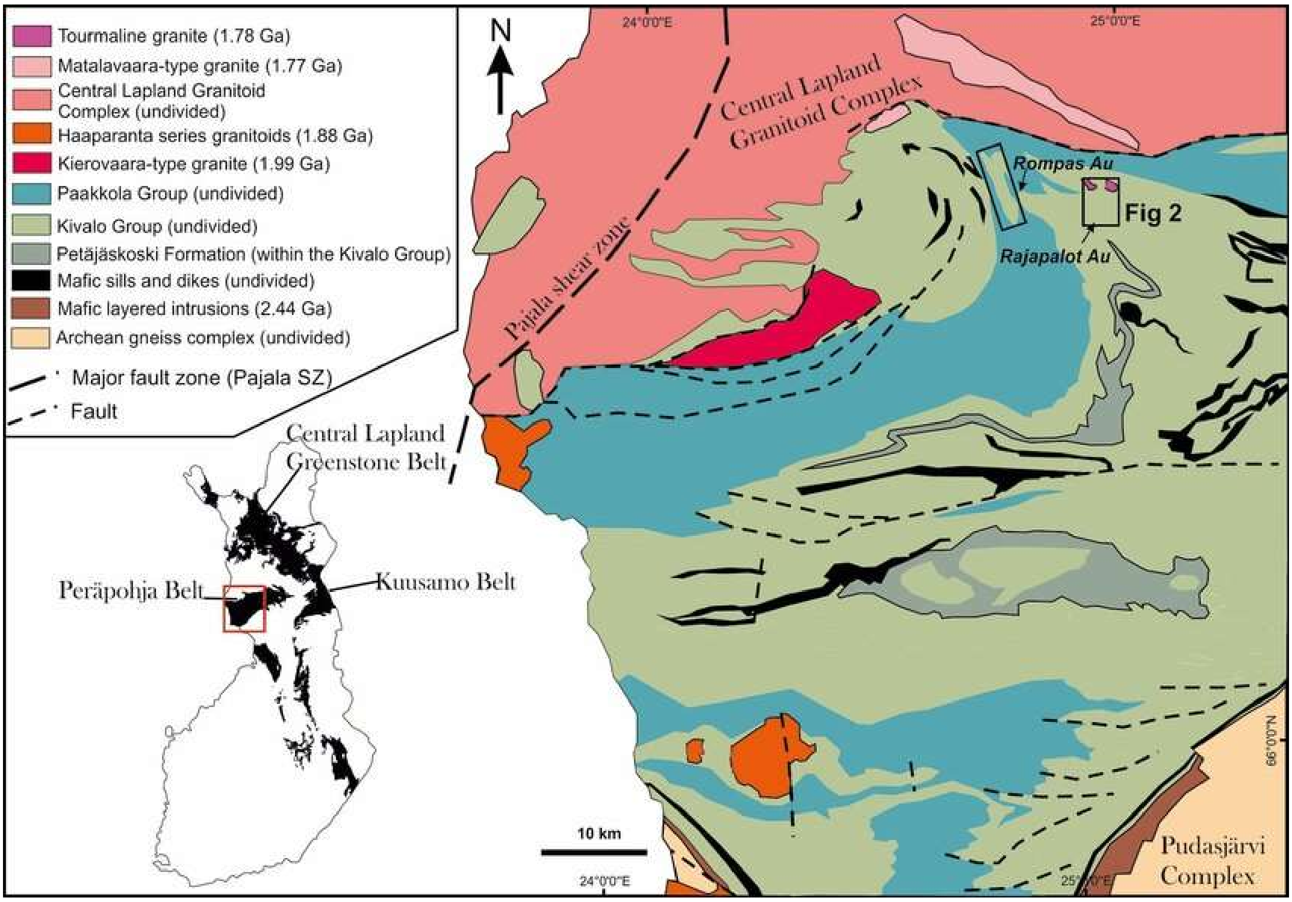


Figure 2 – Geological map of the western part of the Peräpohja belt, Geological Survey of Finland.

Mine Closure Plans

The preliminary economic assessment of the project (PEA) defines the main features of the mine's final closure procedures. The following study phases should include an iterative closure process. In such process information basis is systematically developed to reduce critical uncertainties and to enable gradual improvement of the closure plan. This cycle starts in early project development stages and continues over the whole life-cycle of the mine. The closure plan needs to be confirmed by assessment of post closure impacts and assessment of closure and post closure risks. If impacts (or risks) are at an unacceptable level, review and partial re-planning of closure measures is required.

In Finland, mine closure requirements are largely based on European best available technology (BAT) definitions (MWEI-BREF, 2018), but also relevance of post closure risk and impact assessments – which are also parts of the general BAT-definitions. Best closure planning practices are also generally iterative – repeating same risk and impact assessments in several study phases (ICMM 2019). ICMM also underlines the social perspectives of mine closure (stakeholder expectations).

Post-closure Conceptualisation (outlines)

Key objects remaining on the site after closure are the extractive waste facilities. The company aims to minimize extractive waste rock areas by utilizing waste rock in mine backfill and also in other infrastructure related projects. A project group from Lapland University of Applied Sciences is studying the possibilities of waste rock utilization.

Indicative review of drill core assays of Rajapalot-area, not taking into account mining plan, shows that there is the potential for metal-rich, acid or neutral drainage from tailings. This might be mitigated if two separate tailings areas were established, one for less harmful tailings and another one for waste rock of higher metal/sulphur content with impermeable basal structure. The cover structures are likely to be in line with the basal structures.

Precise closure structures suitable for tailings cannot be estimated at present, due to lack of geochemical data of chosen process option tailings. Based on the ore geochemical quality, and the suggested basal lining, it is likely that the tailings storage facility cover structure will have to be of a low net percolation type, as has been the basis for closure cost estimation.

The aim of planning different structures for waste deposits should be minimal need of seepage water treatment post-closure. Seepage waters containing harmful substances in effective concentrations from waste storage facilities are collected and treated, if necessary, after closure.

Infrastructure will likely be demolished (unless subsequent use is discovered), but road networks typically remain to serve later land-uses, like forestry and reindeer herding. Water management and treatment systems from operational time serve until active closure implementation is completed.

Closure costs for the Tailing Storage Facilities (TSF) and plant areas have been included in the project estimates. At this stage closure requirement considerations are only preliminary assumptions. The EIA and various permits may set additional requirements to the closure measures. Full assessment of closure costs will be completed when the needs are studied in future stages.

4.4 Italy – Monte Tondo quarry

The rehabilitation project is the result of a long process of study and sharing between local administrations, the region, the administration of the protected area (Parco Regionale della Vena del Gesso Romagnola) and the mining company. The general outline of this project made it possible to meet the parameters indicated for the nomination of the area within the UNESCO heritage sites.

The main characteristics of the rehabilitation project are:

- The environmental recovery begins in parallel with mining activity;
- The karst system, internationally known for its unique underground and epigean evaporitic context, is preserved and not further impacted;
- The creation of very steep morphologies more similar to natural ones;
- The protection of vegetation features and bat nesting and refuge sites;
- The creation of paths with panoramic viewpoints;

The exploitation project envisages that at the end of operations there will be a quarry face modelled in berms with a width of 5 m and a height of 10 to 15 m and a slope of approximately 66°.

The morphological and landscape rehabilitation will be oriented to recompose the quarry front according to the natural topography found in the areas not affected by the mining activity (see next photos).

The operations envisaged are as follows:

a. Distribution of inert materials and topsoil on the berms

b. Greening of the berms

c. Greening of slopes

d. Regeneration of surface waters

e. Environmental recovery of the heap of tailings (on the left in the next photo)

Figure 3 – Monte Tondo: the first photo shows the current situation of the quarry, while the second is a simulation of the recovery

a. Distribution of materials and topsoil on the berms

A thickness of debris material will be carried back on the surface of the steps at the base of the slopes in order to mitigate the effect of the artificially steep slope gradients caused by the extractive operation.

Before the placing of the top-soil and the planting of the vegetation, the ‘horizontal’ surface of the quarry berms will be modelled and shaped in such a way as to create an irregular support surface with concavities and undulations to retain the percolating water and thus form a water reserve useful for keeping the soil moist for longer.

b. Greening of the berms

Herbaceous species will be planted on the berms, and shrub and tree species will be planted by hand. The planting will be carried out in an irregular manner, avoiding as far as possible rigid geometric patterns linked to the morphology of the steps, in order to better adapt them to the surrounding environment.

Moreover, in the final phase of securing the escarpments, care will be taken to leave or create cavities of different sizes in the walls that can be used for nesting or resting by birds, in particular diurnal and nocturnal birds of prey.

As far as the plant species to be reintroduced are concerned, they have been chosen from among the autochthonous ones already present in the area, which give the best guarantees of establishment from an ecological point of view and which fit into the lines of the surrounding landscape without creating colour contrasts.

c. Slope greening

In order to create edaphic conditions favourable to the establishment and growth of vegetation, ‘holes’ must be dug on the ‘sub-vertical’ wall of the slope, possibly in correspondence of the marly interlayer, in which the soil must be laid for the planting of suitable plant species.

d. Water regulation

At the base of the escarpments of the berms to be recontoured, there will be no drainage gullies to collect rainwater run-off in order to favour the infiltration and storage of rainwater at the contact between the rock substrate and the backfill soil.

Crop care and monitoring

In order to ensure the success of the operation and the rooting of the plants, it is planned to carry out all the interventions that will be necessary, in particular emergency irrigation until the vegetation proves to be self-sustaining.

In addition, the growth of plant species will be monitored, as well as the possible introduction of other species, and the presence of soil micro- and macrofauna, which are an indicator of the ecological significance assumed or not assumed by the vegetation planted.

Didactic route

With reference to the guidelines stipulated by the Park Plan regulations: "...it is also important, in agreement with the property, to create a scenic, safe pedestrian route with an open-air museum of some significant chalk banks, "cutaways" of dolines intercepted by the excavations...").

The path, approx. 600 m long, winds through a series of thematic features: old quarry fronts (hence 'geological sections'), karst structures of different types (collapse bubbles, erosion 'pipes', etc.), always maintaining a wide panoramic view of the Senio Valley and the old quarry village.

4.5 Portugal – Neves Corvo multi metal mine

An updated Mine Closure Plan was submitted to the Direção-General de Energia e Geologia (DGEG) in December 2022. Following the recommendations of the Environmental Audit in 2016, a two-stage closure-related socio-economic impact study was undertaken and identified expectations from key stakeholders such as local government authorities, community-based organisations, and representatives from business groups, to inform the social transition planning process.

Key closure and rehabilitation solutions include:

- Deposition of soils contaminated with hydrocarbons offsite;

- Placement of metal containing soils on the Tailing Storage Facilities;
- Backfilling of the ventilation shafts followed by plugging with concrete;
- Rehabilitation of mine water level to a pre-mining baseline level;
- Landscaping of the area.

4.6 Portugal – Serra de Candeeiros quarries

Figure 4 – Panoramic view of the Galinha quarry with the main sauropod trackways (IUGS website).

Porto de Mós Ecotrail – Lena's old mine railway

In 1740 the coal extraction from Bezerra's mine started, taking advantage of lignite levels of the Upper Jurassic. In 1928, the only Mountain Mine Railway Line existing in Portugal was built, with a winding route in order to pass over the Pevide sierra (Candeeiros sierra) with a gradient steeper than 2%, whose summit was pierced by the long tunnel of Corredoura, now broken in two. Coming from Martingança, the line passed by Batalha and Porto de Mós, following to Bezerra, near Serro Ventoso, where the coal extracted from this mine and from the one in Barrojeiras (Alcanadas) was loaded. The line also transported goods and passengers, being important for the trade, industry and agriculture of the area. Coal was used in industry, in Porto de Mós thermoelectric power plant (which supplied Porto de Mós and Batalha) and Maceira Cement Company. At the end of the 1940s the railway line closed and was dismantled in 1953.

Taking advantage of the remaining sections of the old railway, Porto de Mós municipality has installed here the Ecopista of Porto de Mós, excellent to walk and to know this vast and beautiful landscape (see Porto de Mós Ecotrail – Lena's old mine railway - Natural.pt).

Natural Monument of Dinosaur Footprints of the Aire Sierra, Ourém

On the eastern flank of the Serra de Aire, around 10 km from Fátima, we find the world's largest and most important collection of sauropod dinosaur footprints from the mid Jurassic period (175 million years old) - Vale dos Meios. Several of the 20 or so tracks, discovered by chance in a former Pedreira do Galinha quarry measure over 100 m in length. The site includes some of the largest and clearest footprints known to date, that attain up to 95 cm in length and 70 cm in width (see Monumento Natural das Pegadas dos Dinossáurios da Serra de Aire, pegadasdedinossaurios.org).

4.7 Sweden – Limestone quarry in Våmb

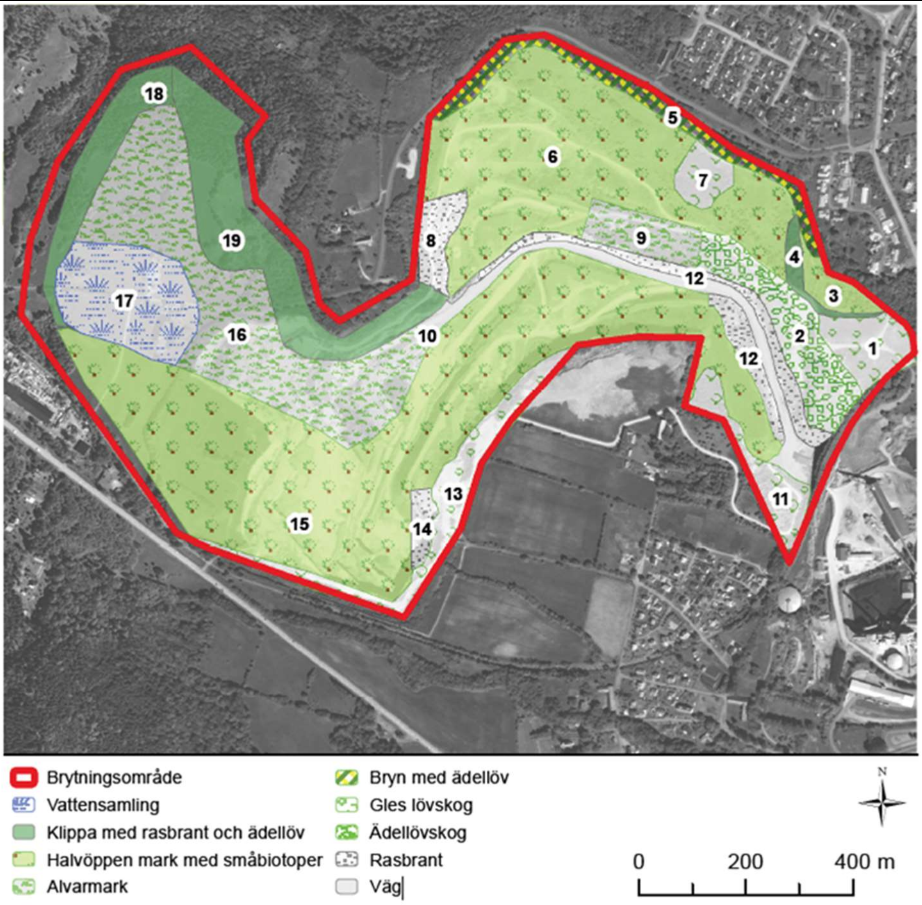
Figure 5 – Limestone quarry in Våmb – Skövde Kommun (web).

General information on aftercare

The proposed measures below focus on favouring the natural values already present in the quarry and creating new natural values in accordance with the conditions that exist in the quarry and in the surrounding landscape. The target biotopes for after-treatment, as described earlier, vary greatly, from low-yield alvar soils, to calcareous wetlands and rich deciduous forest.

However, some general measures can be mentioned that apply more or less to all environments:

- Finely crushed limestone is more favourable for the establishment of vascular plants than coarse limestone;
- Topsoil colonises faster than till, which in turn colonises faster than crushed limestone. Management needs therefore also follow this order;
- Broadleaved trees are favoured over conifers and common deciduous trees (with the exception of willow, whose flowers are important for a rich insect fauna);
- Large trees are favoured over small trees;
- Sun-exposed structures are favoured over shaded structures. Such structures can be trees, shrubs, water surfaces, cliffs, field mounds, cairns and glades;
- Emergent grasses and herbs are kept down by some form of grazing. Mowing is always accompanied by collection and removal of the crop;
- A combination of well thought-out measures, continuous and customised management and a great deal of patience is the basis for the creation of biodiversity;
- Accessibility for the public is a common thread running through the entire aftercare programme. Examples include well-organised paths, signs, viewpoints and barbecue areas.



Brytningsområde = Mining area; Vattensamling = Water collection; Klippa med rasbrant och ädellöv = Cliff with slope and broadleaves; Halvöppen mark med småbiotoper = Semi-open land with small biotopes; Alvarmark = Alvar marrow; Bryn med ädellöv = Brows with broadleaves; Gles lövskog = Sparse deciduous forest; Ädellövskog = Broadleaf forest; Rasbrant = Slope; Väg = Road

Figure 6 – Aftercare plan as in Nilsson C, Lund S., Ström L. (2012). Efterbehandlingsplan för kalkbrottet vid Våmb, Skövde kommun, Sweden – p. 35-52.

Small biotopes and biotope protection

In several areas of the rehabilitated landscape, various small biotopes are planned in a sunlit environment. Examples of small biotopes that will be created are stone walls, field mounds, stone cairns and water environments. Such elements, if located in an agricultural landscape, are covered by the general biotope protection, which means that a special exemption must be sought if an activity will change or damage the biotopes.

Division into sub-areas

Based on how the ground looks today and the conditions that exist in the form of measures already implemented, where masses will need to be placed and, above all, how the various biotopes can be distributed in the quarry to create the most favourable conditions for biodiversity possible, the area, both existing and planned quarry area, has been divided into different sub-areas.

4.8 Conclusions

The pilot cases present in the CIRAN project mostly represent mines in the exploration or excavation startup phase. We have some cases where the excavation area has been partially restored to its original condition (Mittersill in Austria, for example) and others where it was possible to restore the initial environmental conditions (Monte Tondo in Italy). In general, it can be stated that the type of rehabilitation is closely linked to the legislation in force in the State, particularly to environmental regulations. Therefore, general principles and generic standards such as ISO 14001 can be applied and must be followed across the entire mine lifecycle from the initial phases of exploration until the mine “end of life” when extraction activities cease and remediation and rehabilitation become the focal point. If one trend stands out for particular attention as public and regulatory scrutiny of mining grows ever more intense, it is that the mine life-cycle plan should be in place including end of life provision as a condition for issuing the permit at all, and that ongoing or progressive remediation should be seamlessly integrated into operational mining and processing activities.

In Europe, mining activities are subject to a range of regulations and guidelines aimed at mitigating environmental impacts, including provisions for mining rehabilitation. While specific regulations vary by country, there are common principles and frameworks that govern mine site rehabilitation across European jurisdictions. Following these principles and practices scrupulously will be essential for engaging and retaining stakeholder support, maintain investor and regulator confidence, and assuring a flow of data and metrics that satisfy financial and ESG reporting. In more detail, the key components are:

1. **Environmental Impact Assessment (EIA):**

Most European countries require mining projects to undergo an Environmental Impact Assessment (EIA) before approval. EIAs assess the potential environmental, social, and economic impacts of mining activities, including their long-term effects on ecosystems and landscapes. Rehabilitation measures are often included in the EIA process, with requirements for rehabilitation plans and mitigation strategies to minimize environmental harm and ensure the rehabilitation of disturbed areas. The EIA also provides for the definition of a set of indicators of various types, defined to monitor the development of impacts in relation to mining operations. These indicators are also used to verify that the impact mitigation strategies prescribed by the environmental assessment are being properly followed.

2. **Mine Closure Planning:**

European jurisdictions typically require mine operators to develop mine closure plans as part of their permitting process. These plans outline the steps and measures necessary for the progressive reclamation and rehabilitation of mine sites throughout the life of the project and after closure. Closure plans may include provisions for land reclamation, habitat rehabilitation, water management, and long-term monitoring to ensure compliance with environmental standards and regulatory requirements.

3. **Financial Assurance and Bonding:**

Many European countries require mine operators to provide financial assurance or bonding to cover the costs of rehabilitation and environmental remediation in case of default or bankruptcy. Financial assurance mechanisms ensure that sufficient funds are available to implement rehabilitation measures and address any environmental liabilities associated with mining activities. Bonding requirements vary by country and are often based on the estimated costs of rehabilitation and the potential environmental risks posed by the mine. The proper execution of the recovery plan at the end of the mining operation allows the financial guarantee to be discharged.

4. **Regulatory Oversight and Enforcement:**

European jurisdictions have regulatory agencies responsible for overseeing mining activities and enforcing environmental regulations. These agencies monitor compliance with rehabilitation requirements, review closure plans, and conduct inspections to ensure that mine operators adhere to environmental standards and fulfil their obligations for mine site rehabilitation. Regulatory oversight plays a crucial role in ensuring that mining activities are conducted in an environmentally responsible manner and that rehabilitation measures are implemented effectively.

5. **Stakeholder Engagement and Public Participation:**

European regulations often emphasize stakeholder engagement and public participation in the mining permitting process, including discussions about mine site rehabilitation. Public consultation processes provide opportunities for local communities, indigenous peoples, environmental organizations, and other stakeholders to provide input on rehabilitation plans, express concerns about environmental impacts, and participate in decision-making processes related to mining activities. Stakeholder engagement promotes transparency, accountability, and consensus-building around rehabilitation efforts, contributing to the social acceptance and sustainability of mining projects.

6. **Best Practices and Knowledge Sharing:**

European countries promote the exchange of best practices and knowledge sharing in mine site rehabilitation through collaboration with international organizations, research institutions, and industry associations. Best practices encompass a range of techniques and approaches for ecosystem rehabilitation, soil remediation, water management, and community engagement, informed by scientific research, technological innovation, and practical experience. Knowledge sharing initiatives facilitate the transfer of expertise and lessons learned from successful rehabilitation projects, enabling continuous improvement and innovation in mine site rehabilitation practices across European jurisdictions.

Principles and Strategies

In addition, there are common principles and strategies that underpin ecological rehabilitation efforts across the continent.

1. **European Union Directives:**

The European Union (EU) has enacted several directives that influence ecological rehabilitation efforts in member states. The Habitats Directive (92/43/EEC) and the Birds Directive (2009/147/EC) are cornerstone pieces of EU legislation aimed at conserving biodiversity and protecting natural habitats and species. These directives require member states to establish a network of protected areas (Natura 2000) and to take measures to maintain or restore natural habitats and species of community interest.

2. **National Legislation and Policies:**

Individual European countries have their own national legislation and policies governing ecological rehabilitation. These may include laws related to nature conservation, environmental protection, land use planning, and water management. National governments often develop strategies, action plans, and guidelines to implement EU directives and address specific rehabilitation priorities and challenges within their jurisdictions.

3. **Protected Areas Management:**

Many European countries have designated protected areas, such as national parks, nature reserves, and biosphere reserves, which serve as focal points for ecological rehabilitation efforts. Protected area management plans typically include objectives and actions for habitat rehabilitation, species conservation, and ecosystem management. Rehabilitation activities within protected areas may involve habitat enhancement, reintroduction of native species, invasive species control, and sustainable land management practices.

4. **River and Wetland Rehabilitation:**

European jurisdictions prioritize the rehabilitation of rivers, wetlands, and other freshwater ecosystems, recognizing their ecological importance and vulnerability to degradation. The EU Water Framework Directive (2000/60/EC) requires member states to achieve good ecological status in surface waters and to restore degraded aquatic habitats. River rehabilitation projects often involve measures such as dam removal, fish passage construction, riparian vegetation rehabilitation, and floodplain reconnection to improve habitat quality and ecological connectivity.

5. **Landscape-scale Rehabilitation:**

European countries increasingly embrace landscape-scale approaches to ecological rehabilitation, recognizing the interconnectedness of ecosystems and the need for integrated management across diverse land uses and ownerships. Landscape rehabilitation initiatives aim to restore ecological processes, enhance biodiversity, and promote ecosystem resilience at regional or watershed scales. These efforts may involve habitat corridors, green infrastructure, agroecological practices, and collaborative governance mechanisms to achieve shared conservation goals.

5 Permitting and mine site rehabilitation in protected areas

5.1 Systemic permitting

Systemic mine permitting plays a crucial role in facilitating effective rehabilitation processes throughout the mining lifecycle. A well-designed permitting framework ensures that regulatory requirements align with sustainable mining practices, promoting proactive rehabilitation efforts from the outset of operations. By integrating rehabilitation plans into the initial permitting process, authorities can establish clear expectations and benchmarks for mine operators. This approach encourages companies to adopt a life-cycle management perspective, considering closure and rehabilitation strategies during the planning stages. Furthermore, systemic permitting can facilitate adaptive management, allowing for periodic reviews and updates to rehabilitation plans as new technologies emerge or environmental conditions change. This flexibility, coupled with robust monitoring and enforcement mechanisms, helps to ensure that rehabilitation efforts remain effective and aligned with both ecological needs and community expectations. Ultimately, a comprehensive permitting system supports the seamless integration of rehabilitation activities into ongoing operations, fostering a culture of continuous environmental stewardship in the mining sector.

5.2 Principles for mine rehabilitation

Mine site rehabilitation, the process of restoring mined land to its original state or to a condition that supports new uses, is governed by several core principles. These principles aim to ensure the environmental sustainability, economic feasibility, and societal acceptability of the rehabilitation efforts.

Integrating rehabilitation planning into the mine life-cycle planning is essential for sustainable mining operations. It ensures that environmental and social impacts are minimized, and that the site can be returned to a safe and stable condition post-mining. This integration involves several key steps that should be incorporated from the earliest stages of mine planning through to closure and post-closure management.

5.2.1 Exploration and feasibility stage

- **Baseline studies**: During the exploration phase, comprehensive baseline environmental and social studies should be conducted. This data is critical for understanding the pre-existing conditions and for planning effective rehabilitation strategies.
- **Rehabilitation goals**: Define the rehabilitation objectives early, based on stakeholder consultations, regulatory requirements, and the intended future use of the land (e.g., agriculture, recreation, conservation).

5.2.2 Design and planning stage

- **Incorporate rehabilitation into mine design**: Mine design should consider the future rehabilitation process. This includes minimizing land disturbance, planning for the placement of waste rock and tailings in a manner that facilitates future reclamation, and designing slopes and surfaces that are stable and conducive to vegetation growth.
- **Financial Planning**: Establish a financial provisioning mechanism for rehabilitation costs, such as setting aside funds in a trust or a bond. This ensures that resources are available for rehabilitation even if the mine closes prematurely.

5.2.3 Operations stage

- **Progressive rehabilitation**: Implement progressive rehabilitation during the operational phase where possible. This means rehabilitating areas as they become available rather than waiting until the end of the mine life. This approach reduces the environmental footprint during operations and spreads the cost and effort of rehabilitation over the life of the mine.
- **Ongoing monitoring and adaptation**: Continuously monitor the effectiveness of rehabilitation efforts and adjust the strategies as needed. This can include managing water quality, erosion control, and ensuring that re-vegetation efforts are successful.

5.2.4 Closure planning

- **Detailed closure plan**: Develop a detailed closure plan well before the end of mine operations. This plan should include specific measures for dismantling infrastructure, managing tailings, stabilizing the land, and ensuring long-term environmental protection.
- **Stakeholder engagement**: Engage with stakeholders, including local communities, regulators, and environmental groups, to ensure the closure plan meets their expectations and regulatory requirements.

5.2.5 Post-closure management

- **Long-Term monitoring and maintenance**: After closure, ongoing monitoring is necessary to ensure that rehabilitation is successful and that there are no ongoing environmental issues, such as acid mine drainage or subsidence. This phase may require active management for many years.
- **Adaptive management**: Be prepared to adapt post-closure strategies if monitoring indicates that rehabilitation outcomes are not being met. This may involve additional re-vegetation, water treatment, or other interventions.

5.2.6 Regulatory compliance and reporting

- **Regulatory framework**: Rehabilitation planning should comply with all relevant environmental regulations and guidelines. Regular reporting to regulators ensures transparency and accountability.
- **Audits and certifications**: Independent audits and certifications can help verify that rehabilitation has been conducted according to plan and meets the required standards.

5.2.7 Stakeholder and community involvement

- **Community planning**: Involve local communities in planning for the post-mining land use. This can include discussions on how the land will be used, job creation in the post-mining phase, and other community benefits.
- **Corporate social responsibility (CSR)**: Integrating rehabilitation into mine planning aligns with CSR objectives by demonstrating a commitment to environmental stewardship and social responsibility.

5.3 Methods of rehabilitation

Mine site rehabilitation involves various methods designed to rebuild ecosystem function and/or improve land that has been disturbed by mining activities.

These methods form the backbone of effective mine site rehabilitation strategies, addressing environmental remediation, community needs, and regulatory requirements. The integration of these approaches can significantly enhance the success and sustainability of mine site rehabilitation projects, providing a foundation for ecological recovery and post-mining community development.

5.3.1 Landform recontouring

The first step in many rehabilitation processes involves reshaping the mined land to stabilise the terrain and prevent erosion. This includes:

- **contouring**: modifying slopes and creating stable gradients that mimic natural landforms, which help manage water flow and reduce erosion;
- **terracing**: building berms to stabilise slopes and support vegetation on steep surfaces.

5.3.2 Top-Soil remediation

Rehabilitation requires the remediation of soils that have been degraded or contaminated. Effective soil remediation strategies include:

- **Top-soil replacement**: where possible, top-soil that was removed before mining begins is replaced, or if unavailable, suitable top-soil from other sources is used (see Extractive Waste Management Directive);
- **soil amelioration**: enhancing soil quality through the addition of organic matter, nutrients, and pH modifiers to support plant growth;
- **compaction relief**: reducing soil compaction to enhance water infiltration and root penetration for plants.

5.3.3 Revegetation

Revegetation is critical for stabilising soils, supporting wildlife, and restoring ecological balances. This method involves:

- **mapping of plant associations**: local plant associations have to be mapped and assessed for their compatibility with rehabilitation solutions such as capping designs for waste rocks or tailings;
- **native species planting**: using indigenous plants that are adapted to the local environment to ensure higher survival rates and support biodiversity;
- **hydroseeding**: spraying a slurry of seeds, mulch, and fertilisers over large areas. This is especially effective on rough terrains where traditional planting methods are impractical;
- **successional planting**: introducing species in phases that mimic natural ecological succession to create a more resilient ecosystem;
- **remote sensing**: remote sensing using (multi-spectral) satellite or air-borne sensors allows to monitor revegetation success and, if necessary, corrective action.

5.3.4 Water management

Proper management of water resources is essential to prevent contamination and support restored ecosystems. Techniques include:

- **water treatment**: installing systems to treat contaminated effluents from mine sites;
- **construction of wetlands**: creating wetlands to help remove contaminants and treat acid mine or rock drainage, manage stormwater, and provide habitats for wildlife;
- **stream diversion and rehabilitation**: redirecting watercourses affected by mining activities or restoring them to their original courses, and diverting (permanent or perennial) surface water-courses that may compromise extractive waste management facilities.

5.3.5 Waste management

Effectively dealing with mining waste is a critical part of rehabilitation and mandated by the Extractive Waste Directive (EWD, 2006) to ongoing environmental contamination. Strategies include:

- **secure containment**: stabilising and encapsulating hazardous waste materials in lined and covered facilities to prevent leaching and contamination;
- **tailings reprocessing**: some mining waste can be reprocessed to extract minerals that were not economically viable to recover during the initial mining operation;
- **recycling and reuse of extracted materials**: whenever possible, wastes from mining, such as inert mine rubble, should be assessed for potential re-uses, e.g. as construction material.

5.3.6 Monitoring and maintenance

Post-rehabilitation monitoring and maintenance are crucial to ensure the success of the efforts and to trigger necessary adjustments. This includes:

- **ecological monitoring**: periodically checking the health of restored ecosystems, including the success of revegetation and the return of wildlife;
- **water quality testing**: continuously monitoring surface and groundwaters for contamination and adjusting water treatment practices as needed;
- **structural integrity checks**: ensuring that all constructed features (such as terraces, containment structures) remain stable and effective.

5.3.7 Community engagement and development

Incorporating the needs and preferences of local communities into rehabilitation plans ensures the long-term success and sustainability of rehabilitation efforts. This may involve:

- **community consultation**: engaging with local stakeholders to align rehabilitation plans with community needs and values;
- **economic redevelopment**: developing opportunities for economic activities that can benefit from rehabilitated land, such as ecotourism or agriculture.

5.4 Technological approaches in rehabilitation

While a suit of effective and reliable rehabilitation techniques and technologies have been catalogued in the MWEI-BREF (2018), technological innovations play a pivotal role in enhancing the efficiency and effectiveness of mining rehabilitation processes. These technologies not only improve the ecological rehabilitation of mine sites, but also help in monitoring the long-term sustainability of these efforts.

The integration of these technological innovations in mine site rehabilitation brings about more efficient management and enhanced outcomes of such projects. By leveraging modern technologies, stakeholders can ensure that rehabilitated landscapes are returned to their natural state or better, providing environmental benefits and supporting local communities long after mining activities have ceased.

5.4.1 Remote sensing and GIS technology

Remote Sensing and Geographic Information Systems (GIS) are crucial for planning, monitoring, and managing the rehabilitation of mining sites. These technologies allow for:

- **detailed mapping**: accurately mapping the extent of disturbed areas and planning rehabilitation activities more effectively.
- **change detection**: using satellite images and aerial photographs over time to monitor vegetation recovery and landform changes.
- **data integration**: combining soil, topography, hydrology, and biological data to create comprehensive models of the landscape for better decision-making.

5.4.2 Drones and UAVs

Unmanned Aerial Vehicles (UAVs), commonly known as drones, are increasingly used in mining rehabilitation for:

- **high-resolution imaging**: providing detailed aerial photographs and interferometric surveys that help in the precise mapping of site morphologies, vegetation, water bodies, and other landscape features.
- **monitoring**: regular fly-overs to monitor the progress of revegetation and the effectiveness of erosion control measures.
- **spraying**: drones equipped with spray tanks can be used for hydroseeding, allowing for the planting of vegetation in hard-to-reach areas.

5.4.3 Precision agriculture technologies

Originally developed for agriculture, precision technologies can be effectively applied to the rehabilitation of mining sites. These include:

- **soil sensors**: measuring soil moisture, pH levels, and nutrient content to tailor soil amendments and optimise conditions for plant growth.
- **automated machinery**: GPS-guided equipment can be used for precise application of soil treatments, planting, and landscape contouring.

5.4.4 Bioengineering and phytotechnologies

Bioengineering techniques involve the use of living plants and other natural materials to stabilise and restore ecosystems. Phytotechnologies, such as phytoremediation, use plants to remove or neutralise contaminants in soils, water, or air. Innovations in this area include:

- **designer plants**: plants that can tolerate or accumulate heavy metals, making them ideal for growing in contaminated soils.
- **constructed wetlands**: engineered ecosystems that simulate natural wetlands to treat contaminated water efficiently.

Compatibility between the new plant and the surrounding flora must be a cornerstone in the design of the mining rehabilitation.

5.4.5 Artificial Intelligence and machine Learning

AI and machine learning tools are transforming the way data collected from mining sites are analysed and utilised. These technologies enable:

- **predictive modelling**: using historical data and machine learning models to predict the outcomes of rehabilitation efforts and the future ecological impacts of mining.
- **automation of monitoring processes**: AI algorithms can automatically analyse images and sensor data to detect changes in vegetation cover, species diversity, and other ecological indicators.

5.4.6 Virtual Reality (VR) and Augmented Reality (AR)

VR and AR technologies can be used for:

- **visualisation**: helping stakeholders to visualise the expected outcomes of different rehabilitation strategies during the planning phase and before they are implemented.
- **training**: providing immersive experiences for training personnel in rehabilitation techniques without the need for on-site presence.

5.4.7 Internet of Things (IoT)

IoT devices can be deployed across rehabilitated sites to create a network of connected sensors and devices that provide real-time data on:

- **environmental conditions**: monitoring weather conditions, soil moisture, and water quality.
- **wildlife activity**: using motion sensors and cameras to monitor the return of wildlife and assess habitat rehabilitation success.
- **digital twins:** a digital model that captures data from the real-world mine and its processes, simulating the mine's physical assets, operations, and systems, with particular references with the rehabilitation phase.

5.5 Societal and economic aspects

Mine site rehabilitation not only has to address environmental concerns, but also the sometimes profound societal and economic impacts. Effective rehabilitation can help to mitigate the negative effects of mining on local communities and economies, and create new opportunities for growth and development.

The societal and economic aspects of mine site rehabilitation are deeply intertwined with the environmental management. Successful rehabilitation that incorporates comprehensive community engagement and economic planning can transform a purely extractive industry legacy management to a model of sustainable development. This approach not only helps in remediating the environment but also in building a stronger, more diverse economic base for future generations.

5.5.1 Societal aspects

1. **Community involvement and development**: active involvement of local communities in the rehabilitation process is crucial. This engagement helps ensure that the efforts align with local needs and expectations, fostering a sense of ownership and participation. Community input can guide decisions on post-rehabilitation land-use, whether for agricultural, recreational, or conservation purposes.
2. **Health and well-being**: rehabilitation can significantly improve the quality of life for nearby residents by reducing environmental hazards associated with mining, such as air and water contamination. Cleaner environments lead to better health outcomes, reducing the incidence of diseases linked to poor air and water quality, such as respiratory problems and chemical toxicity.
3. **Cultural rehabilitation**: for many local communities, land has cultural, spiritual, and historical significance. Effective rehabilitation can help restore access to these culturally important lands and resources, aiding in the preservation of heritage and traditions.
4. **Education and training**: rehabilitation projects can provide educational opportunities and skills training for local communities. This can include training in ecological monitoring, landscaping, and other rehabilitation activities, enhancing local capacities and employability.

5.5.2 Economic aspects

1. **Job creation**: the process of rehabilitation itself can retain or create jobs, which helps to compensate for the loss of mining jobs as operations wind-down. These jobs can be in areas such as civil-engineering, vegetation replanting, monitoring, maintenance, and management of rehabilitated areas.
2. **Economic diversification**: by converting degraded mining areas into productive lands, communities can reduce their economic dependence on mining. This diversification can include the development of agriculture, forestry, tourism, or other industries, contributing to economic resilience.
3. **Increased property values**: successfully rehabilitated lands can lead to an increase in property values in the surrounding areas. Improved aesthetics and environmental quality make these areas more desirable for residential and commercial purposes.
4. **Attraction of investments**: demonstrating a commitment to responsible environmental practices through successful rehabilitation can enhance a region's reputation, attracting investment not only in mining but also in other sectors. Companies are increasingly attracted to regions that prioritise sustainability, seeing it as indicative of stability and long-term profitability.
5. **Sustainable tourism**: rehabilitated mine sites can become attractions in their own right, especially if they include unique ecological habitats, scenic landscapes, or iconic landmarks related to the former mining activity (like the Cornish mine engine houses). Eco- or cultural tourism can provide a stable source of revenue for local communities long after mining operations have ceased.
6. **Regulatory compliance and incentives:** meeting or exceeding rehabilitation requirements can help mining companies avoid fines and penalties. In some regions, companies may qualify for tax incentives or other financial benefits for demonstrating exceptional environmental stewardship.

5.6 Challenges and barriers

Mine site rehabilitation is a crucial component of sustainable mining practices, but it faces numerous challenges and barriers that can hinder its effectiveness, in particular when the rehabilitation project is not a part of the mine life-cycle. These challenges can be technical, financial, regulatory, and societal in nature, each presenting unique obstacles to the successful rehabilitation of mined lands.

Overcoming these challenges requires a multi-faceted approach that includes technological innovation, financial strategies and strong community engagement. Continuous improvement and adaptation of rehabilitation methods, coupled with international cooperation and knowledge exchange, are essential to enhance the effectiveness of mine site rehabilitation efforts. Enhanced regulatory frameworks, increased funding, and greater awareness and education can help address many of the barriers, leading to more successful rehabilitation outcomes.

1. **Technical challenges**
    a) *complex environmental conditions*: each mining site presents unique environmental conditions, which can complicate rehabilitation efforts. Issues such as soil contamination, water scarcity, or extreme climates can make it difficult to re-establish vegetation and restore ecosystems.

    b) *lack of baseline data*: effective rehabilitation requires detailed baseline data on pre-mining ecological conditions. In many cases, such data may not be available, making it challenging to set realistic rehabilitation goals and measure success.

    c) *innovative technologies*: while new technologies can enhance rehabilitation outcomes, integrating these innovations can be complex and risky. The effectiveness of new methods may not be well-established, posing risks to the long-term success of rehabilitation projects.

2. **Financial Barriers**
    a) *high costs*: the costs associated with mining rehabilitation can be substantial, especially for extensive remediation involving soil treatment, revegetation, and long-term monitoring. These costs may be prohibitive, particularly for smaller mining companies or in regions with lower economic returns from mining.

    b) *limited financial incentives*: in some jurisdictions, financial incentives for thorough rehabilitation are lacking, which can lead to minimal compliance with regulatory standards rather than striving for best practices.

3. **Regulatory Challenges**
    a) *regulatory diversity*: regulatory frameworks for mining rehabilitation can vary widely between countries and even within regions of the same country. Different regulations can complicate compliance for companies operating in multiple jurisdictions.

    b) *lack of enforcement*: even when strong regulations are in place, lack of enforcement can undermine rehabilitation efforts. This may be due to limited resources, corruption, or political challenges in the regulatory bodies.

    c) *evolution of standards*: environmental standards and best practices continue to evolve. Keeping up with these changes can be challenging for mining companies, especially when changes require significant adjustments to ongoing or planned rehabilitation strategies.

4. **Societal Barriers**
    a) *community engagement*: effective rehabilitation requires the involvement of local communities, but gaining community trust and participation can be challenging, especially if past mining activities have negatively impacted the community.

    b) *cultural considerations*: rehabilitation plans that do not consider local cultural and historical values can face resistance, potentially leading to conflicts and delays.

c) *long-term commitment*: mine site rehabilitation is a long-term process, usually extending significantly beyond the life-span of the mining operation itself. Ensuring ongoing commitment and management after mine closure and rehabilitation is a significant stewardship challenge.

5. **Global Challenges**

a) *climate change*: changing climate conditions can affect the viability of rehabilitation methods, especially those dependent on specific environmental conditions. Increased frequency of extreme weather events can also threaten the stability and success of technical rehabilitation solutions and rehabilitated ecosystems.

b) *biodiversity loss: mining can lead to significant biodiversity loss, and restoring it can be particularly challenging. Native species may be extinct or unable to be reintroduced, and invasive species can dominate disturbed sites.*

5.7 Climate change and mining rehabilitation

Climate change poses significant challenges to mine site rehabilitation, impacting the stability and sustainability of rehabilitation solutions and restored ecosystems. At the same time, effectively planned and executed rehabilitation projects can play a role in mitigating some effects of climate change.

5.7.1 Impact of Climate Change on mine site rehabilitation

Environmental Impact Assessment and base-line assessments for mine sites typically rely on climatological and hydrological time-series. Due to climate change, simple extrapolations of past trends may lead to an inadequate dimensioning of remediation solutions or inadequate strategies. More sophisticated methods will be needed to anticipate the effects of climate change, such as:

- **increased erosion and extreme weather events**: climate change leads to more frequent and severe weather events such as heavy rainfall, storms, and floods. These events can erode restored lands, wash away young plants, and undo the progress of rehabilitation efforts. Similarly, drought conditions can inhibit plant growth and reduce the survival rates of newly established vegetation.
- **shifts in ecosystem baselines**: changing temperatures and precipitation patterns can alter the habitats suitable for native plant and animal species used in rehabilitation efforts. This may require the introduction of different species that are more resilient to the new conditions, or adaptive management strategies to help ecosystems adjust.
- **water scarcity**: many regions face increased water scarcity due to climate change, affecting the availability of water for rehabilitation processes such as dust suppression and vegetation growth. This necessitates the development of more efficient water management strategies during and after rehabilitation.
- **soil degradation**: increased temperatures can accelerate soil degradation processes, reducing soil fertility and changing its (bio)chemical makeup. These changes can make it more difficult to establish and maintain plant life.

5.7.2 Mining rehabilitation as a mitigation strategy for climate change

- **Carbon sequestration**: effective rehabilitation, especially through reforestation and revegetation, can significantly enhance carbon sequestration capabilities of mined areas. By planting trees and other vegetation, rehabilitated mines can act as carbon sinks, offsetting some of the greenhouse gas emissions associated with mining operations and other industrial activities.

- **Improving ecosystem resilience**: Rehabilitated sites can be designed to improve ecosystem resilience to climate change. This includes creating more diverse ecosystems that can withstand environmental stresses and adapting land use to anticipated future conditions, ensuring that ecosystems continue to provide essential services like water filtration and habitat provision.
- **Sustainable land management**: Rehabilitation provides an opportunity to implement sustainable land management practices that reduce vulnerability to climate impacts. For example, contouring land to manage water flow can help control flooding and erosion, while choosing drought-resistant plant species can ensure vegetation survival during dry spells.

5.7.3 Future directions for mining rehabilitation in the context of Climate Change

1. **Climate-adaptive planning**: future rehabilitation efforts need to incorporate climate-adaptive planning to ensure long-term success. This includes using climate projections to inform decisions about dimensioning water management systems, cover designs for extractive wastes, landscape contouring, soil profiles, revegetation species selection, and soil amelioration.
2. **Innovative technologies:** leveraging technology such as advanced modelling software, drones for real-time monitoring, and genetically modified organisms can help tailor rehabilitation strategies to be more effective under changing climatic conditions.
3. **Policy integration**: integrating climate change considerations into mining regulations and rehabilitation standards can ensure that mining companies take proactive steps to address these challenges. Policies could require climate impact assessments as part of the rehabilitation planning process.

6 Best practices synthesis

Mine site rehabilitation is an evolving field that requires continuous adaptation and innovation to address environmental impacts effectively and sustainably. As we move forward, several future directions will likely shape the practices and strategies in mine site rehabilitation. These directions not only focus on improving ecological outcomes but also enhancing societal and economic benefits for local communities and broader societies.

The future of mine site rehabilitation is poised to become more innovative, integrated, and community-focused. As the mining industry continues to evolve, so too will the strategies and technologies aimed at ensuring that mined lands are returned to states that are safe, productive, and beneficial for ecosystem networks and human populations alike. Embracing these future directions will be essential for mitigating the environmental impacts of mining and enhancing the sustainability of this critical industry.

1. Integrated land use planning

Future rehabilitation efforts will emphasise integrated land use planning from the outset of mining projects. This approach involves planning the post-mining use of the land before mining even begins, ensuring that the mining process is designed with the end goal of land use in mind. This could mean designing mine operations to minimize environmental impact or pre-planning for land to be converted into conservation areas, agriculture, or mixed-use developments after mine closure.

2. Advanced monitoring and maintenance plan

The use of drones, satellite imagery, and IoT sensors will become more sophisticated, allowing for real-time monitoring of rehabilitation progress and more precise management of ecological variables. Automation in the form of robotic planting and maintenance systems could also reduce the labour costs associated with large-scale rehabilitation projects and improve the efficiency and effectiveness of rehabilitation efforts.

The rehabilitation project must include an appropriate maintenance plan to ensure the effectiveness and efficiency of each intervention over time.

3. Enhancement of ecosystem services

Rehabilitation will increasingly focus on not just restoring ecosystems, but enhancing them to provide greater ecological services than the pre-mining landscape. This includes improving water filtration, carbon storage, and biodiversity beyond original levels to compensate for environmental degradation elsewhere and contribute positively to climate change mitigation efforts.

4. Community-centric approaches

There will be a stronger focus on involving local communities in the rehabilitation process, recognising that sustainable rehabilitation requires local support and involvement. This approach will extend to using local knowledge in rehabilitation planning, providing job training for post-mining economies, and ensuring that the benefits of rehabilitation are shared with the local communities. It is necessary to involve all stakeholders with various types of initiatives (public meetings, focus groups, restricted meetings, ...). These initiatives will initially have the purpose of informing all stakeholders about the activities to be undertaken, but an immediate attempt must be made to involve everyone both in the development of the project, in the evaluation of the impacts and in the final rehabilitation project of the areas and prospects related to the rehabilitation-

5. Policy and regulatory innovation

As the impact of mining on global ecosystems becomes more apparent, there will likely be an increase in international collaboration to develop standardised, stringent regulations for mine rehabilitation. These may include mandatory rehabilitation bonds, clearer guidelines for acceptable post-mining land uses, and stricter penalties for non-compliance.

6. Cross-disciplinary research and collaboration

Future directions in mine site rehabilitation will also involve more cross-disciplinary research and collaboration among scientists, engineers, policymakers, and community groups. This collaborative approach will help develop more comprehensive strategies that address the ecological, social, and economic aspects of rehabilitation.

7. Economic incentives for sustainable practices

To encourage mining companies to adopt more rigorous and innovative rehabilitation practices, economic incentives such as tax breaks, subsidies, and access to international funding could be implemented. These incentives would help offset the initial higher costs of implementing sustainable mining practices and rehabilitation efforts.

8. Bioengineering and phytoremediation advances

Innovations in bioengineering and the use of phytoremediation will likely advance, allowing for the development of more effective ways to deal with soil and water contamination. Genetically modified organisms (GMOs) that can hyperaccumulate heavy metals or that have increased resilience to harsh soil conditions may become important tools in rehabilitation.

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Appendix 1: European regulations pertaining to mining

Table A.1 – Extractive operation life-cycle relevance of EU Directives and Regulations.

Directive / Regulation	**No.**
Environment	
Strategic Environmental Impact Assessment (SEIA)	2001/42/EC
Environmental Impact Assessment (EIA)	2014/52/EU
Environmental Liability Directive	2004/35/EC
Hazardous Chemicals (CLP Regulation)	1272/2008
Water Framework	2000/60/EC
Seveso Directive III	2012/18/EU
IED	2010/75/EU
Habitat	92/43/EEC
Birds	2009/147/EC
Waste	
Waste Framework (WFD)	2008/98/EC
Extractive Waste (EWD)	2006/21/EC
Hazardous Waste Regulations	1357/2014, 2017/997
List of Waste (LoW) Decision	2014/955/EC
Landfill	1999/31/EC
Human Health	
Restrictions of Hazardous Substances (RoHS)	2011/65/EU
Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)	1907/2006
Sustainability	
Renewable energy	2009/28/EC
Renewable energies (RES)	2018/2001
Energy efficiency	2023/1791
Eco-design	2009/125/EC
Eco-management audit Regulation	1221/2009
Societal	
Public participation	2003/35/EC

Table A.2 – OSH relevant EU Directives (see also https://osha.europa.eu/en/safety-and-health-legislation/european-directives).

Subject area	Directive No.
Overarching instruments	
Introduction of measures to encourage improvements in the safety and health of workers at work – OSH Framework Directive	89/391/EEC
Minimum safety and health requirements for the workplace	89/654/EEC
Minimum requirements for improving the safety and health protection of workers in *surface and underground mineral-extracting industries*	92/104/EEC
Minimum requirements for improving the safety and health protection of workers in the mineral- extracting industries through *drilling*	92/91/EEC
Workplaces, equipment, signs, personal protective equipment	
Minimum safety and health requirements for the use of *work equipment* by workers at work	2009/104/EC
Minimum health and safety requirements for the use by workers of *personal protective equipment* at the workplace	89/656/EEC
Minimum requirements for the provision of safety and/or health *signs* at work	92/58/EEC
Minimum requirements for improving the health and safety protection of workers potentially at risk from *explosive atmospheres*	1999/92/EC
Workload, ergonomics, and psychosocial risks	
Minimum health and safety requirements for the *manual handling of loads* where there is a risk particularly of back injury to workers	90/269/EEC
Minimum safety and health requirements at *temporary or mobile construction sites*	92/57/EEC
Working time concerning certain aspects of the organisation of working time	2003/88/EC
On temporary workers	91/383/EEC
Chemical agents	
Chemical agents and its individual Directives 2000/39, 2006/15, 2009/161, and 2017/164 on lists of indicative occupational exposure limit values	98/24/EC
On the protection of workers from the risks related to exposure to carcinogens, mutagens or reprotoxic substances at work	2004/37/EC
Classification, labelling and packaging of substances and mixtures (CLP) of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006	Regulation (EC) No 1272/2008
Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and establishing a European Chemicals Agency	Regulation (EC) No 1907/2006
Biological agents	
On the protection of workers from risks related to exposure to *biological agents* at work	2000/54/EC
Physical agents	
Minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (*vibration*)	2002/44/EC
Minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (*noise*)	2003/10/EC
Minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (*electromagnetic fields*)	2004/40/EC

Subject area	**Directive No.**
Minimum health and safety requirements regarding the exposure of workers to risks arising from physical agents (*artificial optical radiation)*	2006/25/EC
Radiation protection	2013/59/Euratom