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ORIGINAL ARTICLE

Working with Natural Processes: Restoring a Mining Landscape in the High Arctic, Svalbard, Norway

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Abstract
The Svea coal mines in Svalbard have been closed, and the area is under restoration. The goal of the landscape restoration was to enable dynamic ecological and geomorphological processes by removing roads, housing, industrial facilities, airports, landfills, and quarries that once dominated the area. Cultural heritage features, such as pre-1946 buildings, structures, and mining traces, have been preserved, while the rest of the landscape has been restored to a near-natural state. The focus has been restoring geodiversity in this arctic environment, where biotic processes are slow. Geomorphological processes such as glacial, slope, fluvial, coastal, and permafrost processes dominate and give the landscape its geological character. The objective of the restoration is not merely to re-create the landscape's previous appearance but rather to ensure that natural processes can function as they did in the past, contributing to the ongoing development and evolution of all restored land surfaces. As of 2023, most of the area has already been restored. In areas with rapid geomorphological processes, the land will soon be dominated by these processes. Revegetation is one of the major ecological processes the restoration seeks to facilitate. Revegetation is a slow process in arctic environments, and it will take many decades before vegetation covers restored bare surfaces. The project forms a valuable baseline for studying and discussing geomorphology, landscape dynamics, geodiversity, biodiversity, and ecology for nature management and landscape restoration.

Keywords Arctic · Geodiversity · Geomorphological processes · Landforms · Restoration

Introduction

Geodiversity should be an evident component in nature management and, together with *biodiversity*, form a backbone for all nature conservation strategies (Gray et al. 2013). In addition to traditional legal protection, strategies for managing natural environments encompass the restoration of degraded areas, which is the focus of this article.

Geoconservation has a long history as a part of nature conservation (Burek and Prosser (eds) 2008), but traditionally with less prominent position than conservation biology (Crofts 2014). Over the last decades, geoconservation has been more visible in the international debate concerning nature conservation and nature management, through geological initiatives linked to the International Union for Conservation of Nature (IUCN). Several resolutions from the IUCN world congresses have placed geodiversity on par with biodiversity (IUCN 2008, 2012, 2020a), enhancing a more holistic approach to nature conservation. Supporting ecosystem services supplied by geodiversity underpin almost all other ecosystem services. This applies to services directly provided by geosystems as well as services provided by geosystems in interaction with biotic elements (Fox et al. 2020). If geodiversity is neglected in nature conservation theory and practices, this represents a problem for the protection of biodiversity as well as for geodiversity. Geodiversity should therefore be recognized as a vital part of nature in its own right as well as a supporting system for biodiversity and humans.

Geoconservation has traditionally been focused on geosites, a classical conservation strategy where geological or geomorphological sites are valued, selected for conservation, and then (hopefully) conserved or managed to secure the defined values. Geosites are essential, but compared with nature management in its broader sense, single sites are just

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a part of the immense task of conserving and managing nature for a sustainable future. Geodiversity underpins our everyday life and environments on all scales, from the tiniest elements to vast landscapes and continents (Gray 2013). Geoheritage values may be identified on all these scales and through all levels, from local values in our everyday landscapes to international values on the top level defined as world heritage.

Mining is an activity directly dependent on geodiversity; it is also an activity that is often associated with severe negative environmental impacts (Young et al. 2022). Accordingly, the management, conservation, and restoration of abandoned mining sites is a central topic in geodiversity management. In 2020, the World Conservation Congress (IUCN 2020b) adopted a resolution concerning the conservation of natural diversity and natural heritage in mining environments. This resolution "calls on the Member States to conserve mining environments, both underground and surface (open-cast mines and quarries), whose value derived from the conservation of their natural heritage, both geological and biological, is considered greater than the value of their restoration". This resolution is important and highlights the need to analyze each restoration project to ensure that anthropogenic geo- and biodiversity values are not destroyed if these are of higher value than what can be achieved through a traditional restoration. This is an essential element in one of the most critical assumptions for a good restoration project: to clarify and justify its goal (Young et al. 2022).

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES (2018) describes restoration as "any intentional activity that initiates or accelerates the recovery of an ecosystem from a degraded state". Ecological restoration was scientifically rooted in ecological principles and conservation biology (Jordan et al. 1987; Walker et al. 2007), but with a strong focus on management actions and interventions aiming for the recovery of damaged or degraded nature (Palmer and Filoso 2009). Recently, there has been an increased awareness that restoration of land exists within a social context (Junker et al. 2007), and that socioeconomic, political, cultural, and regulatory framework must guide the formulation of restoration goals and choice of methods (Martin 2017; Fischer et al. 2021). During the last decade, ecosystem restoration has been acknowledged in global and regional policy—The UN General Assembly declared 2021–2030 to be the Decade of Ecosystem Restoration, aiming to massively scale up the restoration of degraded and destroyed ecosystems (UNEP 2020). To meet this global ambition, there is a need to expand from small-scale restoration action to large-scale landscape interventions (Hagen et al. 2022).

Traditionally, the international focus on nature restoration has embraced a biocentric approach. Geodiversity is formally included within the definition of ecosystem but is rarely identified as an issue and is often forgotten in management, conservation, and restoration (Knudson et al. 2018; Fox et al. 2020). This is despite the restoration and reclamation of former mining sites getting much attention, such as a separate programme in the European Environmental Agency and formulated mining standards for the Society for Ecological Restoration (Young et al. 2022). The core interest in mining reclamation has primary been pollution and safety issues, followed by biodiversity, ecology, and visual landscape features (Cooke and Johnson 2002). When targeting the reconstruction and design of a post-mining landscapes (e.g. Australian Government 2016; Martin Duque et al. 2020), there is a risk of neglecting the dynamic geomorphological processes. Rather than designing a new landscape, we argue that preparing the future landscape for active geological processes will align with the overall ideas of nature restoration (IPBES 2018).

A greater emphasis on facilitating dynamic geomorphological processes is especially needed in landscapes where geological and geomorphological forces dominate, such as in high Arctic regions with sparse vegetation and slow biotic processes.

This article aims to present and discuss experiences from the large-scale restoration of a coal-mine settlement and associated infrastructure located in the inner Van Mijenfjorden on Spitsbergen, Svalbard (Fig. 1). The project has a strong focus on geomorphological processes and geological landscapes and the link between geodiversity, biodiversity, and landscape diversity. This complex project includes a range of challenging aspects such as pollution management, garbage removal, and mine clearance and closure. However, these issues are not discussed here. This article focuses on landscape and nature restoration which requires a multidisciplinary approach including geomorphology, vegetation ecology and landscape science, as well as a brief discussion of cultural heritage.

Study Area: the Former Mining Settlement Svea in High Arctic Svalbard

Svalbard archipelago is situated in the high Arctic in the Barents Sea, from 74 to 81° north latitude, and from 10 to 35° east longitude (Fig. 1). Regulated within the Svalbard Treaty (1920), Svalbard is a part of Norway. However, habitants of all Treaty Nations (44) have equal access to live and run economic activity within the regulations under Norwegian Laws (Ministry of Climate and Environment 2001).

Since early 1900 up to recent times, coal mining has been the main economic activity in four main settlements in Svalbard: Longyearbyen and Svea (Norwegian) and Barentsburg and Pyramiden (Russian). The coal mine in Pyramiden was abandoned in 1998, and the Svea mine was

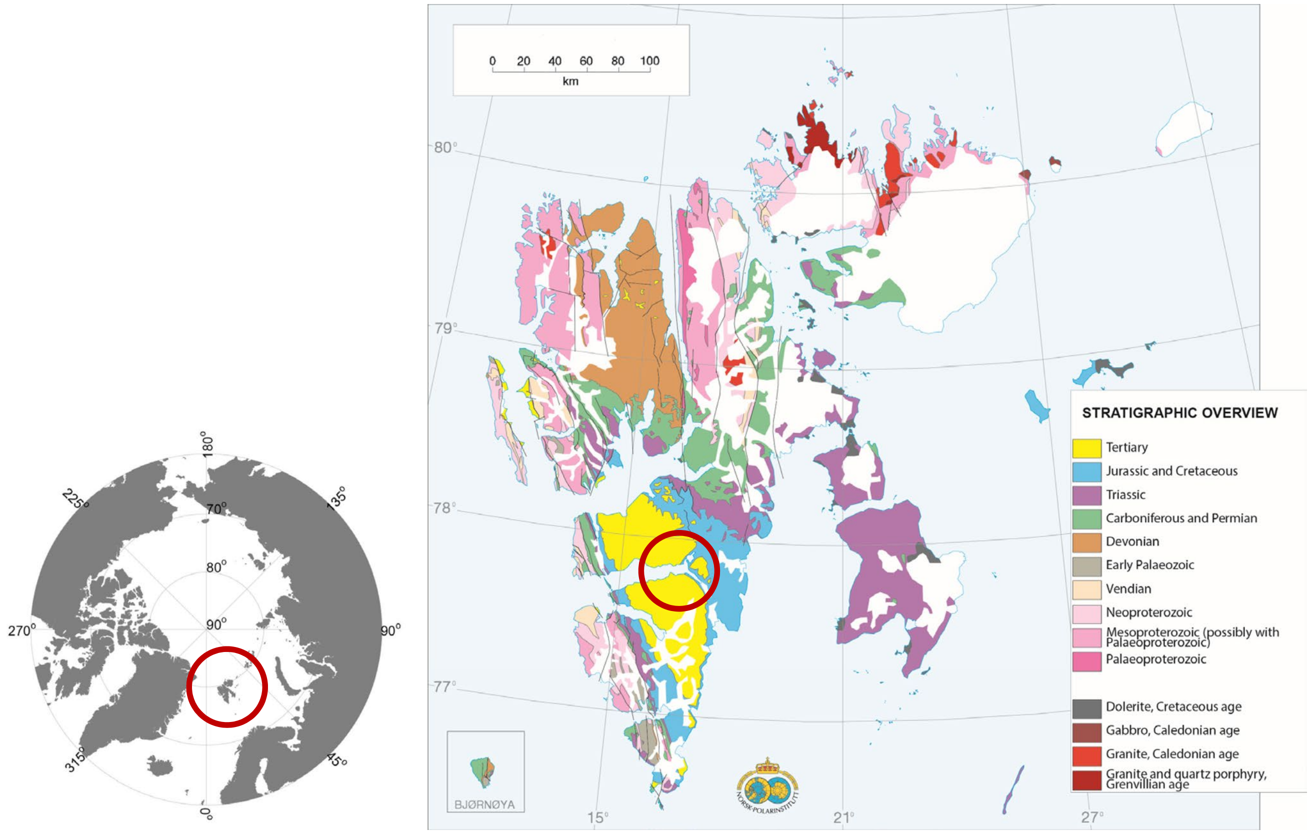

Fig. 1 Geology of Svalbard. Red ring indicates the position of the Svea area. Map from the Norwegian Polar Institute

permanently closed in 2015. At present, 3000 residents from about 40 countries live in Svalbard, mainly in the Norwegian settlement Longyearbyen and the Russian settlement Barentsburg.

Svea (Figs. 2, 3, and 4) is situated 77.5 north latitude southeast of Longyearbyen, Svalbard. Annual mean temperature is – 7 °C and annual precipitation is approximately 300 mm (Norwegian Meterological institute). The total project area for Svea stretches over 20 km from sea level up to 700 m a.s.l. The mountains surrounding Svea exceeds 1000 m a.s.l. (for maps and aerial orthophotos, see https://toposvalbard.npolar.no/). Vegetation on the lowland tundra is up to 15 cm tall and is dominated by bryophytes, graminoids, and herbs. Vegetation coverage and patch size vary; high-altitude areas, steep slopes, and newly deglaciated areas near the mines Svea Nord and Lunckefjell consist of barren land with no vegetation (Elvebakk 2005). The only terrestrial mammals in Svalbard, wild reindeer, and arctic fox, are present in the area. Polar bears visit the area regularly, and whales and seals are abundant in the fjord. A high number of arctic bird species occur and breed in the close vicinity, including arctic grouse, barnacle goose, gull species, and common eider (Kovacs and Lydersen 2006).

Mining History and Closedown for Restoration

Coal mining in Svea started in 1917 and experienced its peak of coal production in two periods from the 1970s and up until today (1970–1987 and 1997–2016). The settlement and mining area stretched over more than 20 km from the shipping port to the most distant and newest mines and included housing, an airstrip, the port, road system, storage areas, workshops, and production areas, in addition to the mines. The mines were based on tertiary coal beds found in the steep slopes in a zone reaching from coastal positions up to high mountain glaciated locations.

In the early 2000s the planning for utilizing the coal beds in the northern part of the area—Lunckefjell—was started. An environmental impact analysis was performed (Hagen et al. 2009) and the plans were accepted. The mine was established, including a road from the existing mines over the glacier Marthabreen to access the Lunckefjell area. The new mine opened in 2014. A prerequisite for acceptance of mining in Lunckefjell was that the area could be restored to «National Park Quality» after mining operations ended.

In the following years, coal prices were low, while the debate over coal production and climate change was intense. In 2015, the Norwegian Parliament decided to close the

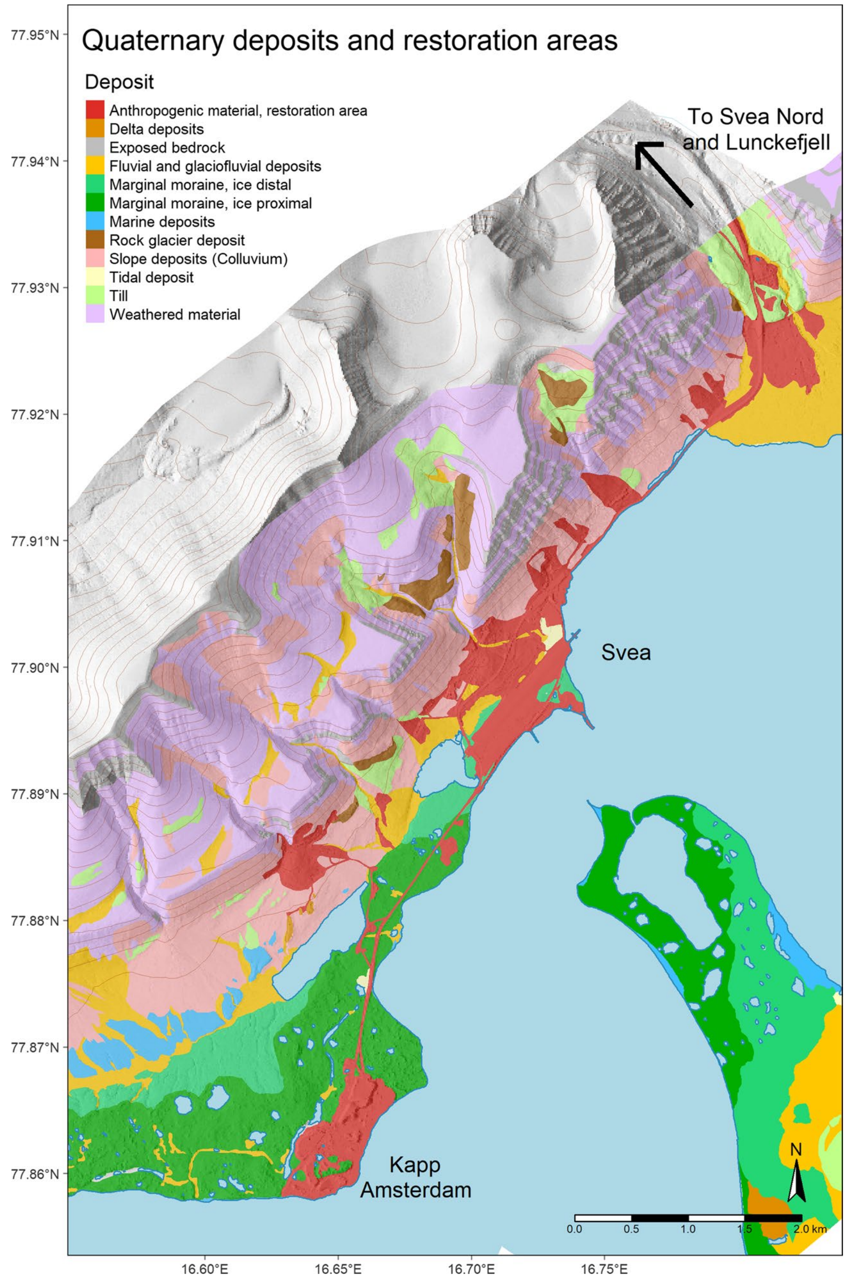

Fig. 2 Quaternary deposits of the Svea area. Superficial deposits and land cover are marked in red. All these areas have undergone restoration leaving only a few houses and structures regarded as cultural heritage. After restoration, the anthropogenic surfaces will be labelled as restored surfaces. Map very simplified from Rubensdotter et al. (2016)

coal-mining activity in the Svea area. It was also decided that the site should be restored to a state as natural as possible, except for objects and areas defined as cultural heritage originating from the early mining activity found in the area and as such protected by law.

The restoration in Svea is mainly governed by the Svalbard environmental act (Ministry of Climate and Environment 2001), where especially Sect. 64 has a key role. It governs clean-up operations and states: "If an activity is closed down or discontinued, the head of undertaking shall take the necessary steps to prevent environmental damage. If the activity may cause environmental damage after it is closed down or discontinued, the Governor shall be given reasonable prior notice of this. When an activity or parts thereof are discontinued, the head of undertaking shall at his own expense remove from the area all surface installations, all waste and other remains that are not protected structures and sites under Chapter V. The area shall as far as possible be restored to its original condition. The Governor may prescribe what measures are to be taken, including whether polluted soil should be treated. The Governor may require that security be provided for the cost of any necessary clean-up operations".

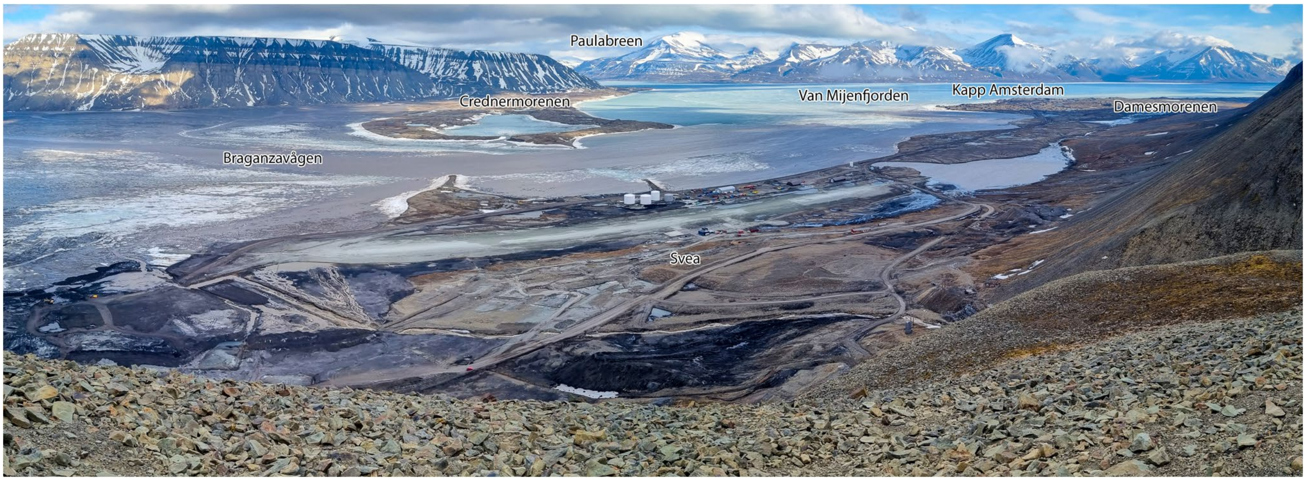

Fig. 3 View down to Svea centre under restoration in 2022. The airport and industrial facilities are visible situated on the section of the Paulabreen moraine complex called Damesmorenen. On the other side of the fjord, Crednermorenen belongs to the same system

Fig. 4 The Svea mines and settlement in 1936. Note the tailing terraces in the upper part of the picture as well as other anthropogenic structures like the houses and transport and port facilities as well as the alluvial fan to the upper right that on this stage still is intact. Photo from www.TopoSvalbard.no

Svea Geology and Landscape

The Svea area is situated in a landscape of flat-lying sedimentary rocks belonging to the Central Tertiary Basin, gently dipping to the west (Elvevold et al. 2007). The bedrock is dominated by layers of Tertiary sand- and siltstones, and relatively thick layers of coal have sustained mining activity here for more than 100 years. The inner part of the Van Mijenfjorden is split into two branches. The northernmost branch forms a large lagoon called Braganzavågen, which is about to be filled with sediments. It is very shallow, and part of a large delta build-out. The southernmost branch ends in a large glacier complex. The main glacier, Paulabreen, had a large surge some 600 years ago (Larsen et al. 2018; Lyså et al. 2018). Under this surge, the glacier blocked the fjord and dammed the valley forming a large freshwater lake and leaving a large ice-cored moraine dominating the shores of the inner Van Mijenfjorden. The landscape is dominated by glacial, fluvial, and periglacial processes in a permafrost setting.

We consider at least two elements of the restoration process in Svea of general interest for restoration ecology. First, what does “restored to its original condition” in the Svalbard Environmental Protection Act mean? This is especially relevant when the Norwegian legal text uses the phrase “original visual appearance”, without referring to natural conditions and dynamic processes. The legal text could therefore be interpreted as static, which would be virtually impossible to achieve in a highly dynamic landscape and thus unintended and unfortunate. The project has therefore focused on facilitating the ongoing natural processes. Where the impact of the mining operations has made an irreversible impact on the land surface, the strategy has been to blend a new landscaped surface in with the surroundings. As the vegetation cover is sparse and geological processes (glacial, periglacial, slope, fluvial, and coastal) are very active, the focus of the nature restoration leans heavily towards geodiversity.

Second, the text makes an exception for protected structures and sites under Chapter V (Cultural Heritage). In Svalbard, all human made structures and sites older than 1946 are automatically protected by law as cultural heritage. This also covers loose items found on the surface or that appear through excavations or natural processes. Accordingly, the restoration objectives for the Svea project involve returning all areas to their natural state while at the same time preserving structures and objects associated with the site's early mining history.

Results

Project Implementation

The restoration project is owned by the state owned mining company Store Norske (www.snsk.no). The authors have served as commissioned advisors on nature and landscape matters for the company. Throughout the project, there has been close collaboration between the company, advisors, contractors, and authorities. The close contact between all parties has fostered a shared understanding of the aims of the projects and decisions have been discussed and reached accordingly. As advisors, we have visited the site regularly and discussed methods and results with the project owner (the mining company) and legal authorities, as well as contractors, including machine operators and other staff involved in the practical work on the ground. To ensure a unified understanding of the area's natural conditions and the restoration's aims and principles, all personnel routinely participated in on-site training courses.

The main strategic decision made by the company and agreed upon by the authorities was to focus on natural processes and enhance the transformation of the surfaces over their respective time scale. Some of these processes occur rapidly while other processes are slow. In certain areas, the extent of the physical changes to the land has made it impossible to restore the landscape to natural conditions. The goal was not to build replicas of static landforms in these areas. When infrastructure and buildings were removed, all natural surfaces were preserved as much as possible. The restored terrain features have been shaped to blend into a landscape that now contain natural, cultural, and restored landscape elements. The construction phase of the restoration includes large-scale redistribution of gravel, stone, and sand, followed by a surface treatment aimed at creating medium-scale variation that promotes vegetation establishment and small-scale abiotic dynamics. The restored surfaces reflect the main form of the previous landforms, based on historical maps and terrain information. Natural landscape elements dominate on a coarse scale. Over time, the restored landscape surfaces will gradually develop their ecological character by natural processes. These transformations range from relatively rapid geomorphological changes on glaciers, shorelines, steep slopes, and fluvial fans and slower transformation in areas affected by periglacial processes and revegetation in tundra areas with gentle, relatively stable surfaces.

The project was divided into three parts: first, the active glacial environments linked to the newly opened Lunckefjell mine; second, the upper parts of the Svea Nord mine areas, also partly in a glacial environment; and last, the central Svea settlement, including buildings, roads, airport, industrial facilities, coal storage areas, and port. As of spring 2023 the work is almost finished. The only remaining works to be done in 2023 are the outer parts of the former coal storage area at Kapp Amsterdam (Fig. 2) and the port area in the same place. The results of the restorations are very diverse both in scale and methodology. The main results are presented here linked to the dominant geomorphic process present.

The landscape is properly documented as it was when a fully operative mining society and the restored landscape will likewise be fully documented when all works are finished. This will work as a basis for future monitoring and research.

Physical Results

We present results for six areas: glacial environments, slopes and screes, coastal areas, glacial forelands, rivers and avalanche fans, and tundra areas. Restored areas are shown on a map given in Fig. 2 with restored areas shown in red. Except for small areas and selected constructions defined as cultural heritage, all these areas are restored and have now changed status to restored areas. Additionally, the road north to the mine Svea Nord over a medial moraine and the road over the glacier between Svea Nord and Lunckefjell mines, together with the mine entrances, have been restored.

Glacial environments Roads and landfills over glaciers have been removed (Fig. 5). Remnants of these structures are still visible as the artificial material has protected the ice from melting. These heightening of the ice surface are expected to melt, and the glacier surface will likely be evened out relatively rapidly. One road was constructed on a medial moraine and has been in operation for a long time. Here road material has been removed from the top of the structure, and the whole structure is expected to melt down over time. The section of the medial moraine where the road was located will exist as a higher and more prominent structure than

Fig. 5 The road and working platform of the Svea Nord entrance after restoration. The working platform has been cleared for all rock material and the heightening of the ice surface will gradually melt. The mine entrance has been filled in and slope processes will gradually shape the surface of the landfill. The road over the medial moraine is still visible but melting processes will collapse the structure. Photo: Martin Øen, Hæhre Arctic

the rest of the medial moraine for many years. The melting process will depend on climatic conditions. Presently, these glaciers are melting quite fast.

Slopes and screes All new mine entrances are situated in scree and steep slopes. Stone has been quarried in the entrance areas. The materials from landfills and roads have been filled in to cover the quarries and entrances and shaped to fit into the terrain on all sides. Slope processes are expected to adjust the detailed surface form, and slush avalanches have already been observed making drainage patterns and levees on these surfaces.

Coast The active, natural processes along the coastline transform the border between sea and land rapidly. Where landfills have been established into the water, material has been moved by machines back onto the land, and the land surface will be moulded by coastal processes. A wide road along the narrow coastline has been removed (Fig. 6). Here, the slope processes affect the restored land surface from one side and coastal processes from the other, helping in the final moulding of the new landscape.

An area with former tidal flat existed outside a fluvial fan in the centre of the Svea settlement. This area has been filled in with tailings. The extent of the landscape changes here has made restoring this area to its original function

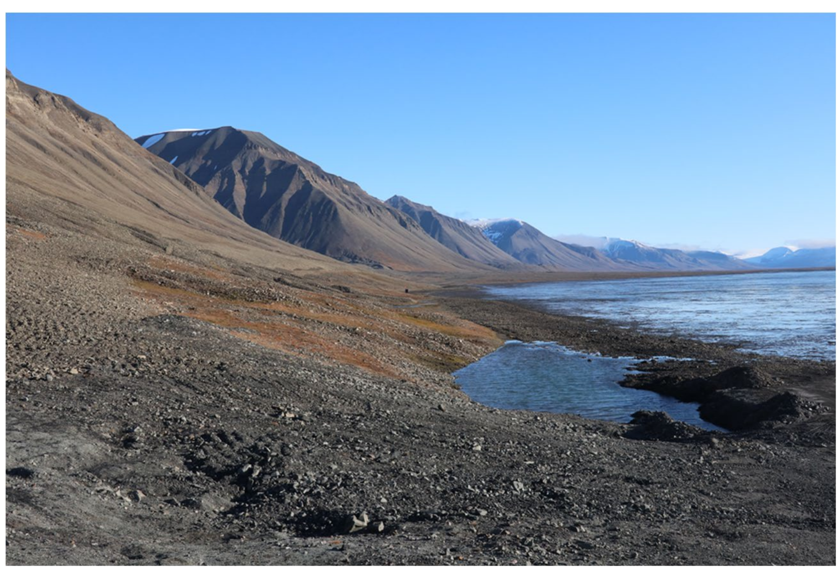

Fig. 6 Restored landscape along the shore of Braganzavågen formerly containing a major coal transport road from the mines of Svea Nord to the harbor. A 10–20 m wide road has been removed from the shoreline

challenging. The terrain has been levelled out, and the outer parts will be modified by the marine processes. The rest will form an artificial terrain surface designed not to dominate the landscape. The area involves the outer part of a fluvial fan (Fig. 4). The fluvial processes here will aid in breaking up the evenness of this adjusted landscape (Fig. 7).

Glacial forelands The airport, the industrial area, and the port and coal storage areas are all situated on the moraine complex from the surge of the glacier Paulabreen. The moraine has two distinct sediment types; proximally a regular non-sorted till, and distally a marine clay-dominated apron pushed up in front of the advancing glacier some 600 years ago (Kristensen et al. 2009; Larsen et al. 2018).

The moraine is partly ice-cored and melting ice has resulted in terrain with hummocks and depressions especially well developed at Kapp Amsterdam. The depressions are partly filled with water. Sparse vegetation cover is found in the depressions, but the hummocks have almost no vegetation, since the winter conditions are too harsh, and the surface is arid. The clay apron has an even surface in places with a shallow system of water erosion riffles. Marine mollusks are common both in the sediments and on the surface. The surface has almost no vegetation cover, perhaps because of the high salt content in the sediments.

The coal storage area (Fig. 8) is an extensive area where the moraine has been entirely transformed. The surface cannot be restored, but the site has been landscaped to blend in with the surroundings. A moderate terrain variation has been applied with depressions and mounds. Replicas of the previous depressions and mounds have deliberately not been created. The natural mounds in the area are at least in parts ice-cored, and melting will result in future changes of these mounds. Many of the depressions have been former ice-cored mounds that have melted. The constructed terrain variation helps the area to blend into the landscape. It affects long-term revegetation by facilitating a mosaic that follows the terrain structures.

The airport runway (Fig. 3) has been constructed on the clay apron distally to the moraine. The terrain has been landscaped to match the former terrain surface. However, the sediments of the clay apron in part of the moraine have been permanently altered and depressed, and marine clay has not been available to use in the construction. Natural recovery of vegetation is extremely slow on marine clay, and as a result, revegetation is expected to develop faster in the restored area than it would on a marine clay surface.

River and avalanche fans Several avalanche fans and fluvial fans occur in the area. The avalanche fans are steep, typically with erosion and levees made by frequent slush avalanches during the snow melting seasons. The fluvial fans are less steep, and the surface is covered by fluvial channels of different ages. Several of the avalanche fans have been affected by the extraction of gravel and stone for construction of roads. The surface of these fans has been restored to, and levelled to a natural gradient, and the upper surface will be moulded by the ongoing natural

Fig. 7 The centre of the former Svea settlement after restoration. Note the airfield is now restored to approximately the same terrain level as originally, and the free running river has started to build a new alluvial fan. Also note the remnants of the old port and a couple of houses to the right preserved as cultural heritage. See also Fig. 3. Photo: Ove Haugen

Fig. 8 The coal storage area and the port before restoration. These areas have been constructed on the rugged moraine surface of the Paulabreen surge. Most of the area was restored in 2022, while the port area will be fully restored during the summer 2023

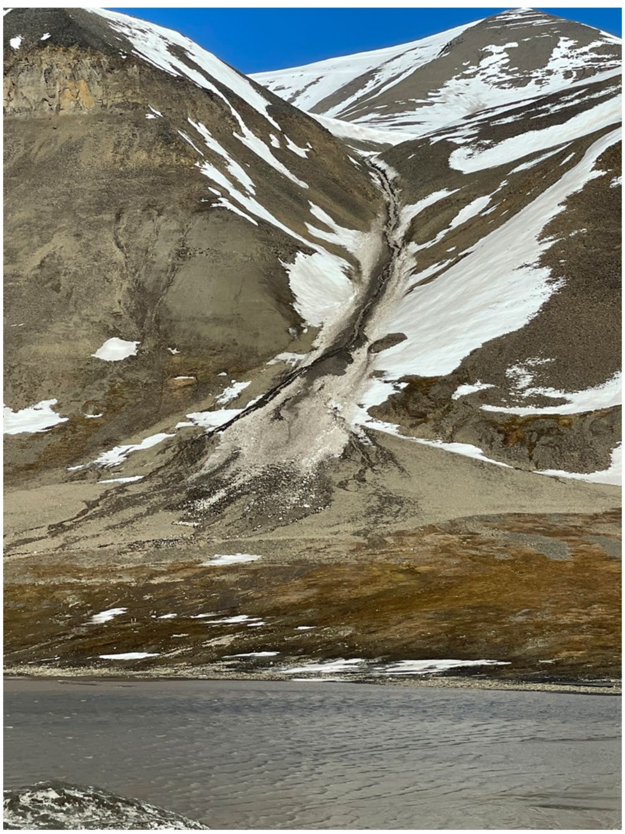

Fig. 9 Resent slush avalanche over a restored avalanche fan surface indicate that natural processes already dominate some restored surfaces

avalanche processes. This has already been observed after the first melting season after restoration (Fig. 9).

A fluvial fan in the centre of the Svea settlement (Fig. 4) will also be affected by slush avalanches in the upper parts and fluvial processes in the lower part. Throughout the mining period, the river was canalized and directed away from constructions and mining infrastructure. Now, canalizations have been removed, and the river runs free (Fig. 7). It is expected to establish fluvial drainage landforms over its former area, although in what timespan this will happen is not sure. Complex landforms and surface processes indicating such development were observed immediately after the first major rainfall.

A large glaciofluvial fan in the fjord's inner part was also heavily affected by gravel extraction, road building, and other activities. A large tailing landfill was established here following a fire in the mine in 2005. During the restoration, the authorities decided not to remove this landfill. The landfill surface has been moderately landscaped and covered with local gravel to blend into the surroundings. The present glacier river has shifted course as the glacier retreated and the surface will therefore not undergo natural transformations from the processes that initially formed it. The restored surface has been designed to seamlessly integrate the landfill with the surrounding fan and will remain this way for the foreseeable future.

Tundra The settlement of Svea was mostly situated on a gently sloping tundra surface, with the main geomorphic activity linked to permafrost and solifluction. The ground is reasonably stable and covered with tundra vegetation when not affected by buildings, roads, and landfills. Most of the buildings were removed in 2021. They were built on stilts (Fig. 10), and the removal of the stilts without leaving

Fig. 10 Removal of houses in Svea in 2021 (left). A typical Svea settlement building to the right

extensive traces in the permafrost environment has been a challenging issue. Some has been drawn up, but the permafrost makes it difficult for those which is driven deep into the ground. The recommended procedure has then been to cut the stilts. If those stilts over time are lifted by frost action, they could be cut again. This procedure has only partly been followed, and in some cases the stilts are digged out, causing damage to some of the minor patches of natural terrain under and close to the buildings.

Three remaining buildings in the Svea settlement are protected by culture heritage protection legislation (Fig. 8). These buildings are being restored and will serve as a resource for future research activities in the area. The area contains many other protected cultural remains, such as railway constructions, an old port, remnants of old buildings, and landfills from the early mines. These archaeological remains have been assessed by experts and will become integral features of Svea's future landscape, serving as enduring reminders of the area's mining history.

The centre of Svea contained a mosaic of "near-natural" surfaces less affected by construction and infrastructure. Most of these sites have been left without any actions. These "near-natural" areas serve as important parts of the new landscape mosaic, contributes to a visually heterogenous landscape and serving as source patches for natural revegetation.

The standard method for removing roads was to remove construction gravel and subterrain tubes and wipe out the straight border between the original landscape and the road, aiming for restoring original mass balance, reshaping the original terrain and wetland structures. In road sections with sparse vegetation, this strategy has worked well but in vegetated tundra terrain where the geomorphological and ecological processes are slow, the sign of former roads will be visible for a long time due to slow natural recovery of the vegetation cover.

Discussion

The restoration of the landscape to " near-natural conditions" in this project has, for a large part, been guided by geodiversity considerations. Biodiversity considerations depended on geological conditions and geomorphological processes. The distribution of vegetation cover and plant communities depends also on small-scale terrain structures, microclimate water movement, moisture, and wind action. Facilitating geodiversity will, therefore, mean appropriate consideration for biodiversity as the abiotic conditions support a mosaic of vegetation cover and habitats as well as landscape character. A multidisciplinary approach for the planning process has been crucial to understand these relations and evaluate potential restoration methods to achieve the project's overall goals. Geomorphology, botany, and landscape knowledge have been on the core of this multidisciplinary effort. The work connected with the natural environment has also been closely connected to the efforts in the project to document and conserve all remnants of the old mining history defined as cultural heritage and all efforts concerning removal and management of pollution in the area. Although not described here, these issues, as well as all activities to remove and handle of interior installations in the mines, have made up significant parts of the overall restoration project.

The project's focus linked to nature restoration has been to facilitate natural processes in a landscape context rather than to conserve specific geoheritage sites and objects. Still, on a landscape level, the vast moraine system from the surging Paulabreen with its deposits, remnants of the damming of an inland lake, and drainage system out along the rim of the glacier has been considered a geosite on international level. The system is well described and studied scientifically (Larsen et al. 2018; Lyså et al. 2018), and the documentation of its significance is solid. The restoration efforts at Svea contribute to the preservation of international geoheritage values related to the moraine system of Paulabreen as a part of a larger geosite in the inner Van Mijenfjorden, and now included in a new National Park, even if the sections with extensive restoration from the airport to Kapp Amsterdam still exist as an island within its border, not included in the park.

Due to safety concerns, it has not been possible to keep access to the underground mines. The geology of the mines has been properly documented, and the mines are situated in the same structures as the mines around Longyearbyen, where there is a population, tourist activity, etc., and where the dissemination of the geological history of this geological area exists and can be further developed. The oldest mining history of Svea will, however, be preserved, as all remains older than 1946 are automatically protected and will remain a part of the future Svea landscape. The modern Svea mining activity and settlement has also been documented and preserved through video material, laser measurements, and material for the Svalbard Museum.

The extensive restoration project at Svea required a consensus on restoration principles for successful outcomes among project leaders and every individual working on the ground. The landscape restoration in a former military training area in a mountain area on the Norwegian mainland served as demonstration in the early stages of the Svea project (Hagen et al. 2022). To foster a common understanding of the project, all personnel participated in “green courses”, gaining insight into the landscape, geodiversity, biodiversity, and restoration principles. Ultimately, the people operating excavators, bulldozers, and dump trucks carry out the restoration work and shape the new landscape; a significant portion of the positive results should be attributed to their efforts.

A restored landscape will not be a natural landscape. For the coming decades, the new landscape at Svea will consist of three main types of landscape elements: natural landscape elements, cultural landscape elements, and restored landscape elements. The definition of geomorphic rehabilitation given by Martin Duque et al. (2019) to replicate “natural” landforms has deliberately not been our aim. We have sought a solution to integrate the restored landscape with its surroundings, but as the land surface has been actively landscaped to avoid landscape contrasts, this difference may be more about philosophy than practical results. Establishing a thorough documentation combining historic map data, aerial photos, Lidar measurements, etc. will secure a solid data source for documentation of the project and a monitoring programme to study future landscape development. It will also ensure that the status and background of all restored landscape elements are known and not mistaken as natural structures. In this way, it will ensure the integrity of the landscape.

Conclusion

With its extreme environment, the geological landscape of Svea is, in many ways, an outlier in restoration ecology. The project forms a valuable baseline for studying and discussing nature management strategies encompassing geodiversity, biodiversity, and landscape dynamics. The relationship between these elements is accentuated in these highly dynamic arctic environments, and therefore make an ideal case for comparison with other landscape restoration challenges across geographic and climatic conditions.

We believe the focus on natural processes belonging to the area’s geodiversity profile has been advantageous for geodiversity and biodiversity. The emphasis on geodiversity has also worked as a platform that secures the affected parts of the moraine system of Paulabreen, considered a geosite of international value.

We believe that the success of a restoration project of this size depends on a multidisciplinary approach, as also demonstrated by other complex large-scale restorations. This goes for the project, including all aspects of the management of the mine’s interior, pollution, cultural heritage, and natural diversity, in which only the latter has been the theme for this article. The success of the restoration leans heavily on the management of the project, and a common understanding of goals and methods established throughout the organization of the project, essentially the running dialogue between project owner, legal authorities, contractors, and experts in landscape, geomorphology, and restoration ecology forms a vital part.

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Declarations

Conflict of Interest The authors declare no competing interests.

References

Australian government (2016) Mine rehabilitation. Leading Practice Sustainable Development Program for the Mining Industry. Industry.gov.au, 69p. https://www.industry.gov.au/sites/default/files/2019-04/lpsdp-mine-rehabilitation-handbook-english.pdf. Accesses 1 Sept 2022

Burek CV, Prosser CD (2008) The history of geoconservation. Geological Society, London, p 300

Cooke JA, Johnson MA (2002) Ecological restoration of land with particular reference to the mining of metals and industrial minerals: a review of theory and practice. Environ Rev 10(1):41–71. https://doi.org/10.1139/a01-014.

Crofts R (2014) Promoting geodiversity: learning lessons from biodiversity. Proc Geol Assoc 125(2014):263–266. https://doi.org/10.1016/j.pgeola.2014.03.002

Elvebakk A (2005) A vegetation map of Svalbard on the scale 1:3.5 mill. Phytocoenologia Band 35 Heft 4:951–967

Elvevold S, Dallmann W, Blomeier D (2007) Geology of Svalbard. Norwegian Polar Institute, 36 p. https://brage.npolar.no/npolar-xmlui/bitstream/handle/11250/173141/GeologyOfSvalbard.pdf?sequence=1&isAllowed=y. Accessed March 2020

Fischer J, Riechers M, Loos J, Martin-Lopez B, Temperton VM (2021) Making the UN decade on ecosystem restoration a social-ecological endeavour. Trends Ecol Evol 36(1):20–28. https://doi.org/10.1016/j.tree.2020.08.018

Fox N, Graham LJ, Eigenbrod F, Bullock JM, Parks KE (2020) Incorporating geodiversity in ecosystem service decisions. Ecosyst People 16(1):151–159. https://doi.org/10.1080/26395916.2020.1758214

Gray M, Gordon JE, Brown EJ (2013) Geodiversity and the ecosystem approach: the contribution of geoscience in delivering integrated environmental management. Proc Geol Assoc 125:659–673. https://doi.org/10.1016/j.pgeola.2013.01.003

Gray M (2013) Geodiversity: valuing and conserving abiotic nature, 2nd edn. Wiley Blackwell, Chichester, p 495

Hagen D, Evju M, Henriksen PS, Solli S, Erikstad L, Bartlett J (2022) From military training area to National Park over 20 years: indicators for outcome evaluation in a large-scale restoration project in alpine Norway. J Nat Conserv 66(2022):126125. https://doi.org/10.1016/j.jnc.2021.126125

Hagen D, Eide N E, Erikstad L, Coulson S, Andersen, R (2009) Coal mining at Lunckefjell, Svalbard. Environmental impact assessment: landscape, vegetation, wildlife and geology. – NINA Report 521, 70 p. https://www.nina.no/archive/nina/PppBasePdf/rapport/2010/521.pdf. Accessed 1 Sept 2022

IPBES (2018) Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In: IPBES secretariat. IPBES, Bonn, Germany, p 44. https://doi.org/10.5281/zenodo.3237392

IUCN (2008) 4.040 Conservation of geodiversity and geological heritage. World Conservation Congress-2008-Res-4.040 IUICN, Gland, Switzerland. https://portals.iucn.org/library/sites/library/files/resrecfiles/WCC_2008_RES_40_EN.pdf. Accessed 1 Sept 2022

IUCN (2012) Valuing and conserving geoheritage within the IUCN Programme 2013–2016. World Conservation Congress-2012-Res-5.048-EN IUCN, Gland, Switzerland. https://portals.iucn.org/library/sites/library/files/resrecfiles/WCC_2012_RES_48_EN.pdf. Accessed 1 Sept 2022

IUCN (2020a) Geoheritage and protected areas. World Conservation Congress -2020-Res-074-EN IUCN, Gland, Switzerland. https://portals.iucn.org/library/sites/library/files/resrecfiles/WCC_2020_RES_074_EN.pdf. Accessed 1 Sept 2022

IUCN (2020b) Conservation of the natural diversity and natural heritage in mining environments. World Conservation Congress -2020-Res-088-EN, Gland, Switzerland. https://portals.iucn.org/library/sites/library/files/resrecfiles/WCC_2020_RES_088_EN.pdf. Accessed 1 Sept 2022

Jordan WRI, Gilpin ME, Aber JD (1987) Restoration ecology. Cambridge University Press, Cambridge, A synthetic approach to ecological research

Junker B, Buchecker M, Müller-Böker U (2007) Objectives of public participation: which actors should be involved in the decision making for river restorations? Water Resour Res 43:W10438. https://doi.org/10.1029/2006WR005584

Knudson C, Kay K, Fisher S (2018) Appraising geodiversity and cultural diversity approaches to building resilience through conservation. Nat Clim Chang 8(8):678–685. https://doi.org/10.1038/s41558-018-0188-8

Kovacs L (ed) (2006) Svalbards fugler og pattedyr. Norsk polarinstituttt, Tromsø, Norway, p 203

Kristensen L, Douglas I, Benn DI, Hormes A, Ottesen D (2009) Mud aprons in front of Svalbard surge moraines: evidence of subglacial deforming layers or proglacial glaciotectonics? Geomorphology 111(2009):206–221. https://doi.org/10.1016/j.geomorph.2009.04.022S

Larsen E, Lyså A, Rubensdotter L, Farnsworth WR, Jensen M, Nadeau MJ, Ottesen D (2018) Lateglacial and Holocene glacier activity in the Van Mijenfjorden area, western Svalbard. Arktos 4(1):1–21. https://doi.org/10.1007/s41063-018-0042-2

Lyså A, Larsen EA, Høgaas F, Jensen MA, Klug M, Rubensdotter L, Szczucinski W (2018) A temporary glacier surge ice-dammed lake, Braganzavågen, Svalbard. Boreas 47:837–854. https://doi.org/10.1111/bor.12302

Martin DM (2017) Ecological restoration should be redefined for the twenty-first century. Restor Ecol 25:668–673. https://doi.org/10.1111/rec.12554

Martin Duque JF, Tejedor M, Martín-Moreno C, Nicolau JF, Sanz Santos MA, Sánchez Donoso R, Gómez Díaz JM (2020) Geomorphic landscape design integrated with progressive mine restoration in clay quarries of Catalonia. Int J Min Reclam Environ 35:399–420. https://doi.org/10.1080/17480930.2020.1844368

Martin Duque JF, Tejedor M, Martin-Moreno C, Nicolau JM, Zapico I (2019) Geomorphic rehabilitation in Europe: recognition as best available technology and its role in LIFE projects, in A B Fourie & M Tibbett (eds), Mine Closure 2019: Proceedings of the 13th International Conference on Mine Closure, Australian Centre for Geomechanics, Perth, 133–146. https://doi.org/10.36487/ACG_rep/1915_12_Duque

Ministry of Climate and Environment (2001) Svalbard Environmental Protection Act. Act of 15 June 2001 No.79 Relating to the Protection of the Environment in Svalbard. https://www.regjeringen.no/en/dokumenter/svalbard-environmental-protection-act/id173945/. Accessed 1 Sept 2022

Palmer MA, Filoso S (2009) Restoration of ecosystem services for environmental markets. Science 325:575–576

Rubensdotter L, Larsen E, Lyså A (2016) Quaternary geological and geomorphological map, Svea, Svalbard Scale: 1: 15 000 Geological Survey of Norway. https://www.ngu.no/upload/Publikasjoner/Kart/Svalbard/KV15_Svea_Svalbard.pdf. Accessed 1 Sept 2022

Svalbard treaty (1920) Treaty between Norway, The United States of America, Denmark, France, Italy, Japan, the Netherlands, Great Britain and Ireland and the British overseas Dominions and Sweden concerning Spitsbergen signed in Paris 9th February 1920. Date of entry into force: 14 Aug 1925. http://library.arcticportal.org/1909/1/The_Svalbard_Treaty_9ssFy.pdf. Accessed 1 Sept 2022

UNEP (United Nations Environment Programme and Food and Agricultural Organization of the United Nations) (2020) Strategy of the United Nations Decade on Ecosystem Restoration. https://www.decadeonrestoration.org/strategy. Accessed 1 Sept 2022

Walker LR, Walker J, Hobbs R J (Eds) (2007) Linking restoration and ecological succession. In: Springer series on environmental management. Springer, New York, p 188. https://doi.org/10.1007/978-0-387-35303-6_8

Young R, Gann G, Walder B, Liu J, Cui W, Newton V, Nelson C, Tashe N, Jasper D, Silveira F, Carrick P, Hägglund T, Carlsén S, Dixon K (2022) International principles and standards for the ecological restoration and recovery of mine sites. Restor Ecol 1–47:30. https://doi.org/10.1111/rec.13771