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# RESTORATION ECOLOGY

## SPECIAL ISSUE: INTERNATIONAL PRINCIPLES AND STANDARDS FOR THE ECOLOGICAL RESTORATION AND RECOVERY OF MINE SITES

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Restoration Ecology Volume 30, Number S2, November 2022

THE JOURNAL OF THE SOCIETY FOR ECOLOGICAL RESTORATION

**Cover:** The life of mine in one photo. A small-scale alluvial diamond mine is in operation on the west coast of South Africa. In the foreground, deep overburdened soil is removed in the operational phase, with post-mined areas being restored in the background. Subsoil and topsoil have been replaced in the top layers, stabilized with windnets and following the first rainy season, annuals and early-succession plant species are establishing. Image credit: Peter Carrick.

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POLICY ARTICLE

# International principles and standards for the ecological restoration and recovery of mine sites

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**Key words: mine closure, mine site restoration, mining, rehabilitation, social license, trajectory**

## EXECUTIVE SUMMARY

Mining has been, and remains, an integral part of human existence from Stone Age quarries through to the iron and coal that fueled the industrial revolution, to the new materials needed to support the shift to renewable energy. Mining and mining products are major contributors to national economies with mining value tripling in the past two decades. As of 2020, the global mining footprint was 57,000 km$^2$ and growing at a faster rate now than any other time in human history. Much of this footprint is operational, but in many areas where mining is now complete, the sites represent major environmental liabilities. Although site stabilization and managing waste materials remains a challenging part of mine closure in many parts of the world, the environmental liability of these sites means more than being just safe, stable, and nonpolluting, with companies increasingly expected to restore ecosystems that are representative of their pre-mined (natural) state. The International Principles and Standards for the Ecological Restoration and Recovery of Mine Sites (Mine Site Restoration Standards, MSRS) present the first international framework for the delivery of socially and environmentally responsible ecological restoration after mining, regardless of whether restoration is legally mandated. The MSRS are designed to inspire and drive higher and better outcomes in post-mining landscapes by both guiding and encouraging the highest level of restoration achievable that supports the global need for protecting and restoring nature. This comes at a time of unparalleled global human impacts where climate change, land degradation and desertification, and biodiversity loss threaten the very ecological fabric of the planet. Mining companies are a major global player in local and regional economies and by demonstrating leadership in protecting, enhancing, and restoring the environments in which they operate, they can maintain, and enhance their social license to operate. The MSRS aim to provide a framework for the mining industry, governments, and stakeholders, including Indigenous peoples and local communities, to address mining-specific issues in delivering effective restoration of mine sites. The MSRS emphasize that achieving the highest possible ecological outcomes depends upon ingenuity, knowledge investment, and a supportive corporate ethos to build a culture of continuous improvement. This approach will maximize benefits for local communities, the environment, and ultimately the mining industry. For industry, the MSRS provide a framework that can be utilized to optimize restoration outcomes that will leave a positive legacy long after mining has ceased. Early adoption of the MSRS by industry can reduce environmental, financial, and corporate risk in achieving site relinquishment by demonstrating the highest possible commitment to stakeholders, increasing natural capital, responding to climate change and land degradation, and recovering biodiversity, including threatened and culturally significant species. The agreed-upon post-mining land use (PMLU), in some cases, is the same general land use that was present prior to disturbance, which often includes fully functioning intact native ecosystems. In other cases, the PMLU may be different from the

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Author contributions: RY, GG, BW, KD, JL, WC formed the core drafting team; RY, GG wrote primary drafts of "Introduction," "Eight Principles that Underpin the Ecological Restoration and Recovery of Mine Sites," and "SoP for Planning and Implementing Mine Site Restoration Projects" sections; RY, VN wrote primary drafts of "Toward a Culture of Best and Future Practice for the Ecological Restoration of Mine Sites" section; in addition to the individual reviewers listed in the acknowledgments, all authors had input to, reviewed, and edited the entire article.

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pre-mining condition. Regardless, the potential for ecological restoration should not be invoked as a justification for destroying or damaging existing native ecosystems. When native ecosystems are impacted by mining, full recovery informed by reference models should be the target. Where this is not achievable a "recovery gap" between the initial native ecosystem and the post-mining ecosystem is created. In highly altered human-dominated landscapes, processes and approaches to mine site restoration may require local solutions but should be undertaken within the Principles of these Standards. When followed, the MSRS can help limit the recovery gap, and where possible (e.g., if mining is implemented in an ecosystem that had previously been highly degraded by other activities), close that gap and move toward net ecological gain. The Standards are underpinned by eight principles that provide a framework to enable restoration decisions that are evidence-based, resilient, and acceptable to mining companies, communities, and stakeholders. They are:

- Engage stakeholders throughout the life of mine.
- Draw on many types of knowledge.
- Be informed by reference ecosystems, while considering environmental change.
- Support ecosystem recovery processes.
- Assess against clear goals and objectives, using measurable indicators.
- Seek the highest level of recovery attainable.
- Gain cumulative value when applied at large scales.
- Employ a continuum of restorative activities.

The MSRS recommend not just best practice, but *future practice* that harnesses the unique investment and technical capacity of the mining industry and applies it toward the most restorative post-mining practices possible. These Standards align with the United Nations Decade on Ecosystem Restoration, the United Nations Sustainable Development Goals, The Mitigation Hierarchy, and international best practice in ecological restoration. They build on the International Principles and Standards for the Practice of Ecological Restoration with key concepts customized to meet the unique challenges of global mining. The MSRS represent a living document that will evolve and develop as technological ability, community and environmental expectations, and understanding of mine site restoration changes over time.

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## Section 1 — Introduction

*Ecological restoration* is defined as "The process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER 2004; Gann et al. 2019).[1,2] The quantity and quality of the ecological restoration and *recovery* of mine sites has accelerated in the past two decades in response to legal and regulatory obligations, community and cultural expectations, and cumulative impacts to landscapes, watersheds, and *biodiversity*. Importantly, mining companies are increasingly aware of the need to maintain their social license to operate[3] (SLO) in addition to legal requirements to achieve mine closure and relinquishment. Thus, there are substantial advances in the corporate intent, scientific knowledge, and technological ability to restore mine sites with the aim of returning healthy, functioning *ecosystems* and landscapes in keeping with local, regional, and global expectations of best practice. However, for many mine sites the lack of guidance on what constitutes acceptable best practice together with a lack of appropriate technical capacity are major impediments to successful mine site restoration.

### Background

Mining is a large contributor to the global economy with the top 40 companies contributing US$544.4 billion in 2020 (PwC 2021). In the mine site restoration context, the mining industry has an unprecedented opportunity to excel in and mobilize significant societal, technological, and financial resources to implement restoration that goes beyond regulatory requirements and actively advances the United Nations Sustainable Development Goals (SDGs)[4] (CCSI, SDSN, UNDP, WEF 2016; IRP 2019). An increasing number of companies (e.g., Anglo-American, Heidelberg Cement) are committed to meeting this challenge; however, many other mining companies are not achieving successful restoration of mine sites (Lamb et al. 2015; Maus et al. 2020) affecting relinquishment and contributing to the growing legacy of abandoned mines. Moving beyond *remediation* and *rehabilitation* to ecological restoration can help reinstate and recover ecological losses as well as increase positive social and community impacts, even beyond the area directly impacted by mining. The opportunity to set new restoration agendas and standards in this field, especially over the next decade, is even more profound as restoration is at the forefront of global efforts to conserve and recover biodiversity and ecological integrity. Implementing *restorative activities* across a continuum of contexts is fundamental to enhance human health and *well-being*; build natural, social, and cultural capital; support Indigenous and traditional land uses; and respond to climate change (e.g., United Nations Decade on Ecosystem Restoration 2021–2030; United Nations Environment Program [UNEP] & FAO 2020; see also section 4, part 3 in Gann et al. 2019).

Direct impacts of mining should be minimized where possible, consistent with the internationally recognized principles of the *Mitigation Hierarchy* (CSBI 2013), where industry and regulators aim to firstly *avoid* environmental impacts; *minimize* impacts that cannot be avoided; when impacts occur to *rehabilitate or restore*; and *offset* any residual negative impacts (Fig. 1). The Mitigation Hierarchy forms a key part of the International Council on Mining and Metals (ICMM) Mining Principles and Position Statements whereby company members commit: "To ensure that potential adverse impacts on biodiversity from new operations or changes to existing operations are adequately addressed throughout the project cycle and that the mitigation hierarchy is applied." Because mining intact or near intact ecosystems creates a *recovery gap* that usually cannot be addressed by mitigation alone or even mitigation plus restoration, offsets are often used to try to address residual mining impacts. However, the current application of offsets rarely, if at all, can achieve like-for-like or net gain outcomes for impacted ecosystems. The Mine Site Restoration Standards (MSRS) therefore are founded on (1) reconsidering if and where mining occurs (e.g., prioritizing mining in areas that have previously been converted[5]) and avoiding unique or high-value natural and cultural assets; (2) minimizing the recovery gap to the extent possible by implementing the highest level of restorative activities beyond achieving a safe, stable, and nonpolluting landform; and (3) conducting off-site recovery of legacy mines and other adjacent degraded landscapes in order to move toward ecological and social *net gain* by restoring more than what was impacted. The MSRS outline how to minimize the recovery gap to the extent possible by implementing best practice and *future practice* that builds a company's SLO and minimizes closure risks.

In many jurisdictions a mining company is legally required to manage, return, or transfer the land to a custodian or owner in a condition that matches an agreed *post-mining land use* (PMLU) in accordance with regulatory requirements.[6] When the PMLU includes a *native ecosystem*, *ecological restoration* is often required. The MSRS describe how ecological restoration and *allied activities* should be undertaken in these mining landscapes to achieve the highest level of recovery possible given site conditions and societal choice. The MSRS and other relevant regulatory documents (e.g., EMPs) and guidance (e.g. ICMM 2019) should be used in tandem to maximize efficiencies and cohesion within the activities of the mining company,

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[1] Ecological restoration activities in mining literature may be described using several different terms, including reclamation (see Table 1).

[2] Terms in italic face are defined in the Glossary section.

[3] SLO is a term used widely in the mining industry. Here, in the MSRS, we use the term specifically in the context of license to operate or close, with the intent to optimize social and environment performance.

[4] The SDGs are the blueprint to achieve a better and more sustainable future for all. They address the global challenges faced, including those related to poverty, inequality, climate change, environmental degradation, peace, and justice. The 17 Goals are interconnected, with the aspiration to be achieved by 2030.

[5] Remnant native vegetation, even when degraded, has significant value within highly degraded and fragmented landscapes and therefore should be protected during mining operations whenever possible, in addition to being prioritized as focal sites for ecological restoration. These patches could comprise remnant native ecosystems, traditional cultural ecosystems, or semi-natural ecosystems, that may also (or through translocation) contain global, national, or local threatened species. See also Principle 3 in the International Standards.

[6] Compliance documents required to manage mining impacts vary according to region, with each country and state having their own conditions. Some regions have high levels of environmental compliance required, while others operate with little regulatory oversight. Compliance documents can include environmental impact assessments (EIAs), environmental management plans (EMPs), and mine closure plans (MCPs).

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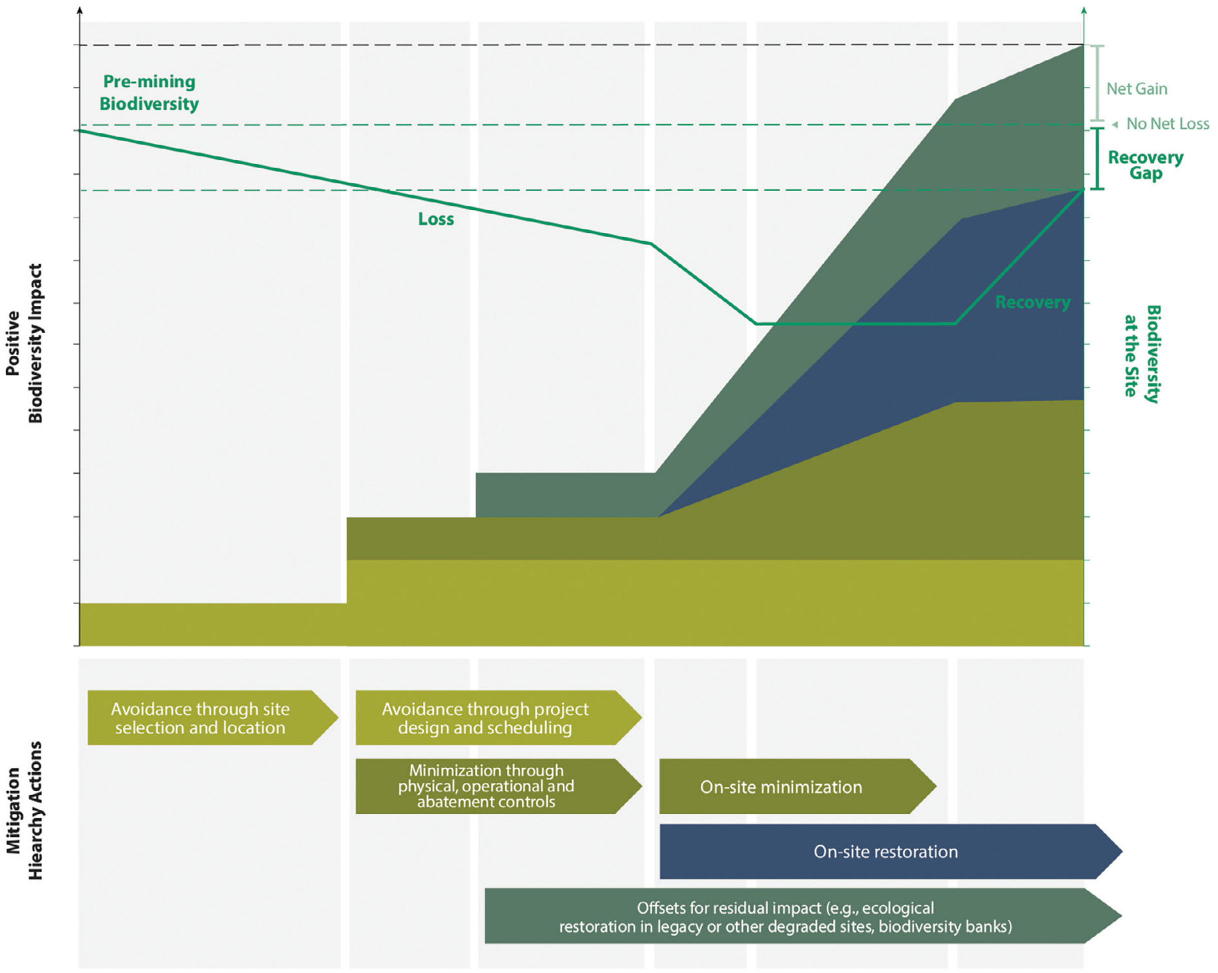

Figure 1. The *mitigation hierarchy* as it pertains to native ecosystems and biodiversity represented as a continuum when mining in an intact native ecosystem. In order to achieve no net loss (NNL) or net gain, a company will need to assess the potential impacts associated with a planned development and secure stakeholder agreement before designing mitigation measures throughout the project cycle to mitigate for that impact. Impacts should first be avoided (light green) as a priority, then minimized to the greatest extent possible (olive green). *Progressive restoration* on site (dark blue) is needed to further reduce impacts, but these measures are still unlikely to achieve NNL. Biodiversity offsets (dark green, such as ecological restoration in legacy or other degraded sites, are needed and considered as a last resort to compensate for any residual impacts remaining to achieve NNL or net gain. The timeline for mitigation relative to the project timeline is illustrative and can vary depending on the context (adapted from White et al. 2021).

recognizing that the MSRS will most often exceed established regulatory requirements.

Recognizing that the environment and social context represents the number one key risk for the mining and metals industry in 2022 (Ernst & Young 2021), Environmental, Social, and Governance (ESG) performance is becoming a critical reporting measure for mining companies. Obtaining and complying with government approvals and regulatory requirements alone may no longer be sufficient, nor socially and culturally acceptable, when implementing a new mining project (Box 1). Challenges to obtaining an approval for a new mine can be exacerbated when agreed outcomes for *reclamation*, rehabilitation, or *mandatory restoration* have not fully been delivered by the mining company on previous projects. Instances of mining developments being delayed, interrupted, or not approved due to community opposition are increasing. As such, mining companies must be diligent in building, fostering, and maintaining currency of their SLO through open and full disclosure of their technical and financial capacity to deliver an agreed post-mining outcome (Moffat & Zhang 2014). Furthermore, the sustainability agendas of mining companies through ESG structures, including *climate readiness* is now a key driver for financial investors (Eccles & Klimenko 2019). The majority of international financiers and many mining companies have adopted the Equator Principles,[7] and are signatories to the UNEP Principles for Responsible Banking (UNEP Finance Initiative 2019), the Task Force on Climate-related Financial Disclosures,[8] and the forthcoming Taskforce on Nature-related Financial Disclosures.[9] These principles require recipients of banking loans, including mining

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[7] https://equator-principles.com/
[8] https://www.fsb-tcfd.org/
[9] https://tnfd.global/

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### Box 1. Guiding tenet

*The potential for ecological restoration should never be invoked as a justification for destroying or damaging existing native ecosystems or for unsustainable use* (Gann et al. 2019).

Many mines and extractive industries operate in native ecosystems,[10] including wetlands, coastal environments, forests, tropical grasslands, and subalpine ecotones, some of which are of high or irreplaceable conservation values. Mine sites also present some of the most challenging settings for ecological restoration due to the significantly altered geological profile (Buisson et al. 2019; Festin et al. 2019). To date, full recovery of native ecosystems has only been achieved on a small percent of the area where global mining activities have degraded or destroyed native ecosystems, even when the technological and operational potential exists (Lamb et al. 2015; Maus et al. 2020). Thus, if mining approval is based on restoring a functional and resilient native ecosystem based on a reference model, proponents should demonstrate adequate site and ecosystem-specific technical ability to restore before commencing the mining activity.[11] If this cannot or has not been done in advance, early investment in establishing the restorative approaches and *adaptive management* structures to deliver a restoration outcome by the time of mine closure should be required. This can be achieved through research, adaptive management, and progressive restoration.

companies, to align their business strategy with the SDGs and the Paris Climate Agreement (United Nations 2015).

Although other documents speak to the practice of ecological restoration and repair, or the process of mine closure, the MSRS for the first time, consolidate guidance and provide an integrated framework for best practice. By adopting the MSRS and expanding commitment to ecological restoration and allied *restorative activities*, mining companies can ensure that the social and environmental benefits extend beyond the mine itself, while building sustainable prosperity.

## Abbreviations

| | |
|---|---|
| AER | annual environmental report |
| EIA | environmental impact assessment |
| EMP | environmental management plan |
| ESG | Environmental, Social, and Governance |
| ESIA | environmental and social impact assessment |
| FAIR | findable, accessible, interoperable, reusable |
| FPIC | Free, Prior, and Informed Consent |
| ICMM | International Council on Mining and Metals |
| ILK | Indigenous and local knowledge |
| IPBES | Intergovernmental Platform on Biodiversity and Ecosystems Services |
| IUCN | International Union for Conservation of Nature |
| LoM | life of mine |
| MCP | mine closure plan |
| MSRS | Mine Site Restoration Standards |
| NNL | no net loss |
| PMLU | post-mining land use |
| SDGs | Sustainable Development Goals |
| SEA | strategic environmental assessment |
| SER | Society for Ecological Restoration |
| SIA | social impact assessment |
| SLO | social license to operate |
| SMART | specific, measurable, achievable, results-oriented, and time-limited |
| UNEP | United Nations Environment Program |

### Scope and Organization of the Document

The Society for Ecological Restoration (SER) and partners published the International Principles and Standards for the Practice of Ecological Restoration (Gann et al. 2019) (International Standards), which are foundational to the design, implementation, monitoring, and evaluation of *ecological restoration projects* at all scales and in all ecosystem types worldwide.[12] Core to the International Standards is the Restorative Continuum that articulates that ecological restoration is one of a range or family of restorative activities that can support the recovery of *ecosystem integrity* (Gann et al. 2019). However, mines and mined landscapes present unique challenges often not encountered in many restoration projects. Hence, the need for a complimentary document of ecological restoration and recovery of mine sites.

An essential precursor to successful restoration at mine sites is the attainment of a safe, stable, and nonpolluting landforms. This is typically a large and complex engineering challenge, requiring significant knowledge and financial inputs. Detailed closure planning throughout the *life of mine* (LoM) including the characterization of the physical, chemical, biological, and ecological properties of the site is needed to effectively manage mine waste, mine drainage and water, post-mining landforms, and impacts and risks associated with mine tailings, radiological, or other hazardous materials. Elements of achieving a safe, stable, and nonpolluting landscape as a phase of mine closure are discussed, as they impact the success of restoration, but the topic itself is not comprehensively addressed in the MSRS as it is effectively covered in other documents (LPSDP 2016*a*, 2016*b*; Global Tailings Review 2020; Salvador et al. 2020).

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[10] In the MSRS native ecosystems include certain types of traditional cultural ecosystems and semi-natural ecosystems (see Definitions below, and Principle 3 in Gann et al. 2019).

[11] Old growth components of native ecosystems such as old trees and cavity-nesting fauna can take decades to centuries to return to a landscape and thus high value areas should be avoided with mitigation strategies, such as buffers, applied around significant zones.

[12] The peer-reviewed International Standards (second edition) is a key document in the official Strategy of the United Nations 2021–2030 Decade on Ecosystem Restoration (United Nations 2020), and in the Decade Principles (FAO, IUCN CEM & SER 2021). It is available in English, Chinese, French, Spanish, Portuguese, and Ukrainian with further translations underway.

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The MSRS focus on the restoration of areas impacted by mining and present the established and emerging knowledge from scientific research, as well as practical and collective experience. The MSRS include all forms of terrestrial activities but exclude subsea mining. They apply at varying scales and extent in pit, underground and strip mining for minerals, raw materials, coal, peat, oil, and gas, where terrestrial environments are impacted. Relevant concepts and tools in the International Standards are customized to meet the recovery and restoration challenges of mine sites (e.g., key definitions, the Eight Principles, *Five-star System*, Social Benefits and Ecological Recovery Wheels), together with additional concepts and tools consolidated from other leading guidance documents (International Finance Corporation 2012; Liu & Clewell 2017; ICMM 2019; Young et al. 2019; Liu et al. 2021).

This section (Section 1) provides the background and scope of the document. Section 2 considers how the MSRS can be adopted into the LoM process and move toward a culture of best and future practice. Section 3 outlines the eight key principles that underpin the ecological restoration and recovery of mine sites. Section 4 covers mining-related standards of practice (SoP) for ecological restoration. Throughout this article, global case studies are used to demonstrate key concepts of the MSRS in practice.

Appendix S1 of the MSRS provides full versions of the case studies used in the manuscript. Appendix S2 includes a series of pertinent issues and explanatory concepts relevant to topics discussed in the manuscript including: SLO; legal frameworks; Indigenous rights; the economic, social, and environmental value of restoration; the Mitigation Hierarchy and ecological offsets; repurposing; developing reference models; achieving safe stable and nonpolluting landforms; water management; implications of climate change; and monitoring and evaluation.

### Additional Definitions and Terms

Ecological restoration is distinct from *restoration ecology*, the science that supports the practice of ecological restoration, and from other forms of environmental repair in seeking to assist recovery of native ecosystems and ecosystem integrity. Ecological restoration aims to move a degraded ecosystem to a trajectory of recovery that allows adaptation to local and global changes, as well as persistence, ultimately enabling continued evolution of its biodiversity and functionality. Ecological restoration is part of a continuum of restorative activities that, under certain conditions, comprise the broad concept of *ecosystem restoration* as defined by the UN Decade on Ecosystem Restoration: *the process of halting and reversing degradation*, *resulting in improved ecosystem services and recovered biodiversity*. *Ecosystem restoration encompasses a wide continuum of practices*, *depending on local conditions and societal choice* (UNEP 2021). The MSRS accept ecological restoration as any *activity* with the goal of achieving ecosystem recovery relative to a native *reference model*. Other kinds of restorative activities, such as mine reclamation, may also refer to reference conditions, but those references may return agricultural or other land uses. Reference models used for ecological restoration projects in mining are informed by a native *reference ecosystem* appropriate to the altered *substrates* and environment, which can include *traditional cultural ecosystems* or *semi-natural ecosystems*. Reference models do not necessarily describe intact native ecosystems, but alternative stable states that could be considered following mining (see Principle 3). Ecological restoration is commonly used to describe both the process and the outcome sought for an ecosystem, but the MSRS use the term *restoration* for the activity undertaken and *recovery* for the outcome sought or achieved.

Ecological restoration projects or programs at mine sites include one or more *targets* that identify the native ecosystem to be restored, and project goals that establish the level of recovery sought. *Full recovery* is defined as the state or condition whereby, following restoration, all *key ecosystem attributes* closely resemble those of the reference model. These attributes include absence of *threats*, physical conditions, *species* composition, community structure, ecosystem *functions*, and *external exchanges*. Where lower levels of recovery are planned or occur due to resource, technical, environmental, or social constraints, *partial recovery* is the planned goal. At the minimum, an ecological restoration project or program should aspire to *substantial recovery* of the native biota and ecosystem functions (contrast with rehabilitation and other terms in Table 1). *Progressive restoration* involves the staged restoration of disturbed areas during the exploration, construction, and resource extraction phases of a mine, instead of large-scale works at the end of the project. *Mine closure* occurs when all mining activities have ceased, but the mine owner remains responsible for environmental compliance of the site. *Relinquishment* is achieved when the formal approval by the relevant regulating authority is granted (all obligations have been met satisfactory to authorities and possibly other stakeholders) and transfer of ownership and residual liability can shift to that agency or a third party. At this point, when ecological restoration is the goal, the site should be on a demonstrated recovery *trajectory*.

When full recovery is the goal, an important benchmark is when the ecosystem demonstrates *self-organization*, which is when almost all of the necessary elements are present, and the ecosystem's attributes can continue to develop toward the appropriate reference state with minimal outside assistance, or even benefit from traditional cultural practices. Once self-organization is achieved, if unexpected *barriers* or other factors take recovery off-course, restoration interventions may be required to ensure the trajectory continues toward full recovery. Certain activities that occur during restoration, for example, weeding and watering new plantings, can be referred to as *aftercare*. Once fully recovered, any ongoing management activities (e.g., maintenance of *disturbance regimes*) would be considered as *ecosystem maintenance*. Specific activities, for example the control of invasive species, may be used in both the restoration and maintenance phases of a mine restoration project.

In the mining industry, terms such as reclamation, rehabilitation, *remediation*, *repurposing*, and *revegetation* are commonly used, often interchangeably, but each are distinct processes (Table 1; Fig. 2; Principle 8) and care should be taken to use the appropriate terminology for a given activity. *PMLUs* are land uses that occur after the cessation of mining operations, which can require ecological restoration, reclamation, rehabilitation, or repurposing to be achieved. A diversity of stakeholders should be involved in determining the PMLUs before mining commences; however, evolution of PMLUs may occur throughout the LoM, reflecting changing stakeholder or PMLU holder desires.

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**Table 1. Common terminology used in the mining industry in relation to restorative practices (adapted from Gann et al. 2019; ICMM 2019).**

| *Term* | *Definition* |
|---|---|
| Ecological Restoration | The process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (Gann et al. 2019). Ecological restoration differs from other types of restorative activities in that it aims to assist in recovering the ecosystem to the trajectory it would be on if degradation had not occurred, accounting for environmental change. |
| Ecosystem Restoration | The process of halting and reversing degradation, resulting in improved ecosystem services and recovered biodiversity. Ecosystem restoration encompasses a wide continuum of practices, depending on local conditions and societal choice (United Nations 2021). |
| Mitigation Hierarchy (as it pertains to native ecosystems and biodiversity) | The sequence of actions to anticipate and avoid, and where avoidance is not possible, minimize, and, when impacts occur, restore, and where significant residual impacts remain, offset for biodiversity-related risks and impacts on affected communities and the environment (CSBI 2013) |
| Offsets (biodiversity, ecosystems) | Measurable conservation or restoration outcomes, resulting from actions applied to areas not impacted by the project, that compensate for significant, adverse project impacts that cannot be avoided, minimized, and/or restored (CSBI 2013). |
| Reclamation | A broad term used to describe multiple post-mining activities but often relates to the process of reconverting disturbed land to its former or other productive uses. In some areas, it may be synonymous with or a subset of rehabilitation, whereas in others, it is more closely related to and may include ecological restoration. In the USA, reclamation "implies that *the site is hospitable to organisms that were originally present or others that approximate the original inhabitants* (National Research Council (U.S.) 1974), but it also has been used to describe conversion of degraded areas into lands suitable for agriculture, livestock, or water production. |
| Rehabilitation | Management actions that aim to reinstate a level of ecosystem *productivity* or functioning on degraded sites, where the goal is renewed and ongoing provision of ecosystem services rather than the recovery of a specified target native ecosystem. Rehabilitation is encouraged and valued where it: (1) improves ecological conditions and functions; (2) is the highest standard that can be applied at present; and (3) improves conditions that could lead to recovery of a native ecosystem in the future. |
| Remediation | Management actions that aim to remove degradation (e.g., detoxify areas with contaminants or excess nutrients from soil and water) to achieve safe, stable, and nonpolluting landscapes. It is a pre-requisite for ecological restoration, reclamation or rehabilitation following mining. |
| Repurposing | The process of identifying a new use for a mine site, either in whole or in part, that takes advantage of site characteristics to provide an economic or social activity post-closure, or other post-closure land use (e.g., light industry, recreation, solar or wind farms). Repurposing can involve any of the above activities and is sometimes synonymous with reclamation. |
| Revegetation | A process of establishment of plants and vegetative cover on sites (including terrestrial, freshwater, and marine areas) that may or may not involve local or *native species*. |

## Section 2 — Toward a Culture of Best and Future Practice for the Ecological Restoration of Mine Sites

### Social License to Operate[13]

In many parts of the world, maintaining a SLO is critical to the success of a mining company. As a concept and practice, SLO originated in the mining industry and has evolved over 25 years. SLO represents a highly diverse array of disciplinary and conceptual influences—including anthropology, psychology, philosophy, law, management, governance, ethics, communication, and human rights—to form a complex, dynamic, and often contested discourse. Ernst and Young's (Mitchell 2020) list of risks and opportunities in the mining sector is regularly headed not by physical, tangible matters, but by the SLO. This prioritization may derive from the relative intangibility of SLO, combined with the challenge of unambiguously defining the concept, which may seem to have a disproportionate influence on a company's perceived legitimacy. Indeed, SLO's apparent intangibility suddenly becomes very real when faced with rebuilding community trust following incidents such as the blasting of 46,000-year-old rock shelters at Juukan Gorge (Commonwealth of Australia 2020) or the catastrophic loss of life and livelihoods due to tailings dam collapses (Owen et al. 2020).

Despite (or perhaps because of) the relatively extensive literature, the development of SLO remains a challenge for many companies. Although some adopt effective processes during early project development, more often social and community activities (e.g., assessment, engagement, monitoring) occur in a relatively piecemeal or disconnected manner through an operation's lifecycle, with a focus on engagement in the "front end" rather than ongoing relationship-building and social performance monitoring. Once a project is approved, companies often become more transactional in their community interactions, confusing a community's tolerance of a project in the assessment phase with ongoing approval; a community's cooperation with trust; or technical credibility with social legitimacy.

Communities hosting mining operations expect to benefit materially or in other ways from the presence of mining projects. Where mining companies operate, their local communities

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[13] The Social License to Operate section was written by Richard Parsons (New South Wales Government) and Dr. Sheridan Coakes (Umwelt Australia). A full discussion on the topic is provided in Appendix S2a.

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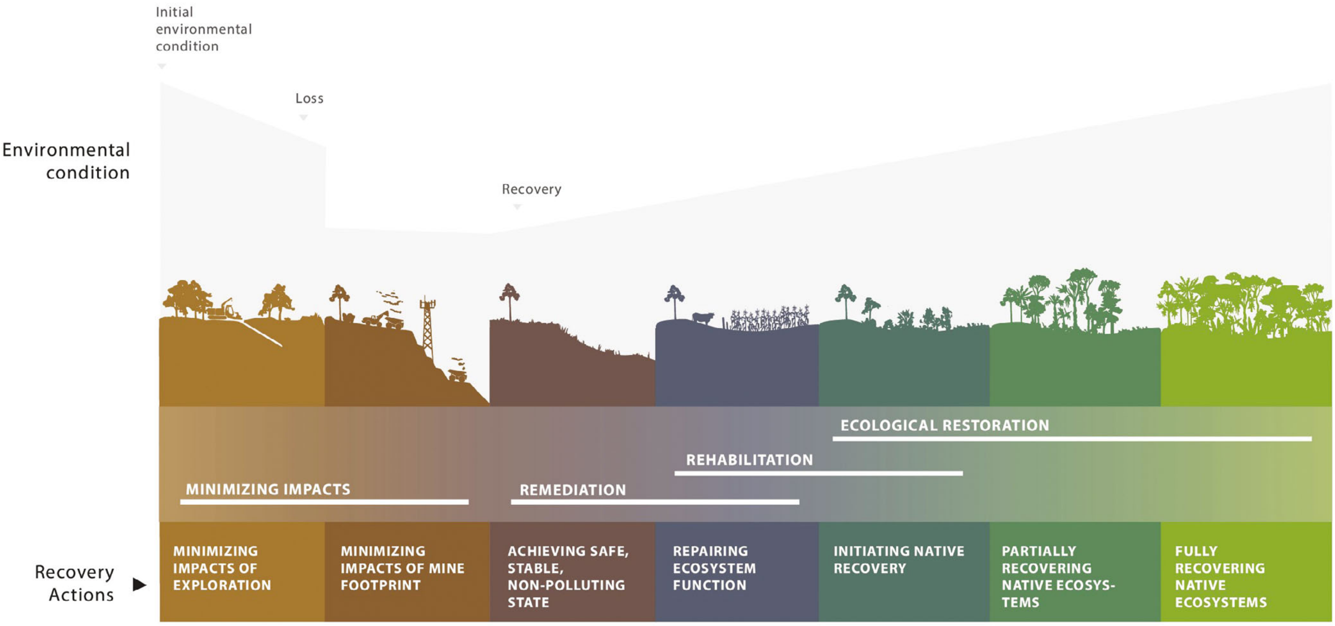

Figure 2. *Recovery trajectory* for mine sites, including associated categories of restorative activities at different life of mine stages. Adapted from the Restorative Continnum in Gann et al. (2019) and discussed in Principle 8.

expect genuine, respectful, fully transparent, and life-of-mine relationships, not just involvement when approvals or consents are required. Host communities also expect industry to be good neighbors that contribute consistently and genuinely to local community dialogue and issues; and who work in partnership with communities to enhance natural, physical, economic, social, and human capital thereby leaving a positive social and environmental legacy when mining is complete. High levels of SLO have been achieved. For example, Veenker and Vanclay (2021) evaluated the Dutch oil company NAM and assessed the highest level of social license (psychological identification) using the Thomson and Boutilier's scale (Thomson & Boutilier 2011). Despite NAM industrializing a rural landscape over time, and contributing to change in community composition, cohesion, and identity, the company delivered material and long-term local benefits and developed respectful and responsive local relationships. The result was that people in the community of Schoonebeek trusted NAM to do the right thing and to take responsibility for their actions, even following major incidents.

There is no universal approach to the development of social license. Each community has its own histories, cultures, narratives, norms and conventions, specific issues, power dynamics, systems of knowledge, and interests, all of which can change over time. Companies need to know their host communities well, respect Indigenous and local knowledge (ILK), develop trusted relationships both with key stakeholders and "ordinary" community members, participate actively in community life, and deliver on their promises, as key prerequisites for SLO. Once lost, SLO is extremely hard to regain. Communities have enduring memories, and trust and respect is earned, not given. See Parsons and Coates (2022) in Appendix S2a for further discussion on the SLO in mining.

### Establishing the Trust Model in Mining

The process of change toward a culture of social and environmental best practice can often be long, requiring "company champions" to work diligently and continuously. The best environmental outcomes are achieved when trust is first established between government (regulators), industry, community, and science, and then leveraged to go beyond best practice (Fig. 3). The "Trust Model" can be difficult to attain and sustain, but once established the best net environmental, social, and operational benefits can be realized.

Science and ILK are both fundamental to ensuring that robust and independently verified information guides mining businesses toward better environmental outcomes. It is important to acknowledge that these outcomes will continue to improve as new knowledge is developed and embedded into company practice (future practice, Box 2). Science interactions that embrace long-term relationships yield greatest results, as detailed knowledge of a site is progressively developed and an understanding of how the biota respond to the altered conditions is established (Principle 2 in Section 2 expands on the important role of science).

Throughout the LoM, companies engaging in restoration must maintain active engagement with government agencies, local communities, and stakeholders. Importantly, dialogue with regulators is critical when risks of restoration failure mean alternative pathways or changes in the standard operational procedures are required. When government

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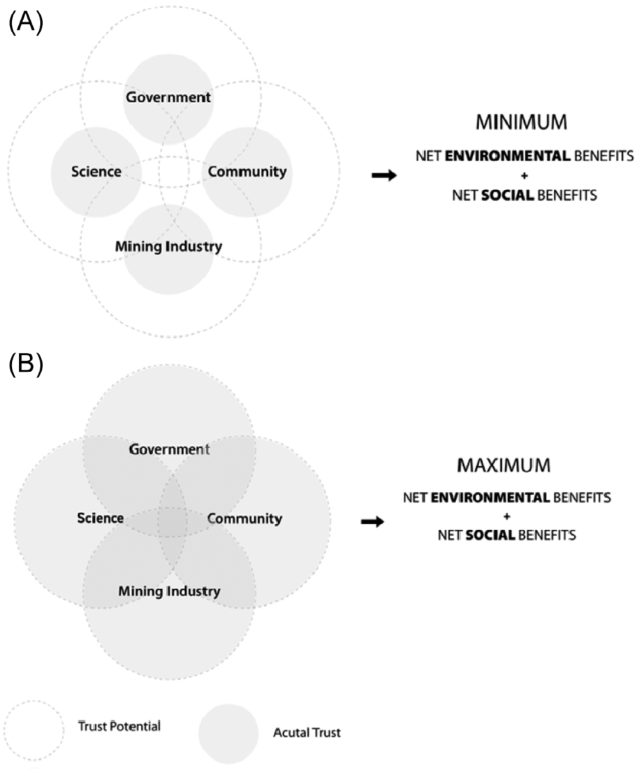

Figure 3. The *trust model for delivering best practice* restoration of mine sites. Each interaction must be genuine, open, and transparent with science providing the independent oversight needed for communities and regulators to have confidence in the quality of the information being provided. If there are (a) low levels of trust between the mining company and stakeholders, the environmental and social benefits are compromised, as opposed to (b) high levels of trust where environmental and social benefits can be maximized.

**Box 2. Future practice.**

Future practice is the acknowledgment that aspects of science, ILK, on-site learning, and other knowledge sources that are not currently known or understood will inform, influence, and improve restoration practice in the future including the cost-effectiveness of restoration. Companies adopting future practice will build monitoring and review into company policy that enables evidence-based management and practices to develop improved outcomes, even when those changes are currently unknown.

regulators and stakeholders are included in a process of information exchange with companies throughout the LoM, it will be easier for companies to gain approvals for restoration plan modification (adaptive management) to achieve outcome-based objectives. Furthermore, this can create an environment of trust (Fig. 3) whereby regulators are more supportive of industry and science innovation for restorative approaches.

### Legal Frameworks[14]

Mine closure governance is increasing globally. This is in response to greater societal awareness of the economic, environmental, cumulative impact, and social consequences of abandoned and ineffectively closed mines and the sustainable development agenda in mining (APEC 2018).

However, the global adoption of mine closure and restoration regulations is inconsistent, with some jurisdictions having little or no regulatory controls in place, while others have a robust governance framework (APEC 2018). Where financial assurance mechanisms are in place, the "polluter pays" principle of environmental law is intended to protect the public in the event the mining company is unable to meet its environmental obligations (Peck & Sinding 2009). A common regulatory requirement in mining jurisdictions is for the operator to post-financial assurance for rehabilitation costs in case of a default. The nature of this assurance varies, and may include instruments such as sureties, collateral, or self-guarantees (e.g., company guarantees), but these mechanisms are not always effective. For example, such "bonds" are often inadequate to cover abandonment costs or for unplanned events such as landslides, pollutant control, and impacts on watersheds. Where liabilities transfer to governments in the case of a company defaulting on mine closure, governments are expected to fund the rehabilitation and closure costs (Mackie & Besco 2020).

Closure also presents complex social impacts where a mine has provided local employment and business opportunities (Mfune et al. 2020). Legal frameworks presently lack comprehensive governance of social transition, but aspects may be included in requirements for EIAs, social impact assessments (SIAs) or combined environmental and social impact assessments (ESIAs), as well as in mine closure plans (MCPs). Although complying with legal frameworks, companies must also ensure these frameworks represent best industry practice benchmarked by international standards otherwise companies may risk their own and industry-wide SLO. Therefore, a challenge for industry is knowing what robust and sustainable mine closure is, particularly where regulatory frameworks are weak or lack clarity. It falls to the company to understand what is expected by communities and to ensure they exceed compliance when possible (Deloitte 2020). This is consistent with the SLO concept.

Mine closure and restoration legislation may not explicitly address ecosystem recovery relevant to closure or may fail to address key ecological processes or conditions needed to reach desired future condition. Thus, companies need to ensure their legal frameworks for closure management match current and future societal expectations beyond minimum standards that include clear evidence of sustainability. As the mining industry enters a phase of closure, regulators will seek to improve the efficacy of mine closure governance, such as changing financial assurance risk profiles and incentivizing progressive rehabilitation. Mining companies need to be anticipate that environmental

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[14] The Legal Frameworks section was written by Lauren Downes and Prof. Alex Gardner (University of Western Australia). A full discussion on the topic is provided in Appendix S2b.

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standards will increase as governments and society increase awareness of what environmental legacy remains after mining ceases. See Downes and Gardner (2022) in Appendix S2b for further discussion on mine closure legal frameworks, regulation, and policy.

### The MSRS, Regulations, and Other Guidance

Governance and regulation at national and regional levels for managing environmental impacts, restoration, and mine closure is highly variable across the globe. As a result, the level of scrutiny of environmental impacts and restoration outcomes are inconsistent across political boundaries (World Bank Group 2021). Organizations such as the International Organization for Standardization (ISO), the Intergovernmental Forum on Mining, Minerals and Sustainable Development (IGF), the Global Reporting Initiative (GRI), and ICMM provide best-practice guidance addressing mine site reclamation or rehabilitation (see World Bank Group 2021 for a summary of leading guidance) but none of these resources address the restoration principles and process in detail, particularly for native ecosystems, a gap the MSRS fills.

During the approvals stage, government regulators apply rules and regulations intended to manage environmental impact from mining and to regulate post-mining land condition upon closure. Mining companies are required to report on adherence to these rules and regulations throughout the LoM. The names, contents, and purpose of these documents are globally variable but generally can be categorized as per the below.

**Environmental Impact Assessment.** Environmental Impact Assessments (EIAs) review the likely environmental impacts of a proposed project or development, considering interrelated environmental, socioeconomic, cultural, and human-health impacts, both beneficial and adverse (CBD 2017). Generally completed during the approvals stage, EIAs aim to predict environmental impacts at an early stage in project planning and design, find ways and means to reduce adverse impacts, shape projects to suit the local environment and present the predictions and options to decision-makers. The information generated during this process can be integral to inform the reference model (Principle 3) for restoration. Thus, to maximize company efficiencies in integrating restoration in mine planning and to ensure adequate resourcing, these assessments should be completed with the aim of informing mine approval and closure, as well as restoration opportunities.

**Strategic Environmental Assessment.** A Strategic Environmental Assessment (SEA) covers a wider range of activities or a wider area and often over a longer time span than project-level EIAs. A SEA can apply to an entire sector or to a geo-political area. Typically, a SEA does not replace or reduce the need for a project-level EIA (although in some cases it can), but it can help to streamline and focus the incorporation of environmental concerns (including biodiversity) into the decision-making process, often making the project-level EIA process more efficient. A SEA can improve planning and contextualization of mine site restoration within the broader landscape. Like EIAs, SEAs should be undertaken with the intention that the outcomes inform mine approvals, closure, and restoration. The information obtained can and should be used to plan and prioritize mine site restoration in a manner that optimizes ecological outcomes and creates net gain for natural assets (Principle 7).

**Environmental Management, Reclamation, and Restoration Plans.** Documents that outline the planning, implementation, monitoring, and post-implementation process for a mine site restoration project include EMPs, reclamation plans, and ecological restoration plans. A plan may reflect statutory obligations agreed to between the company and regulatory authority or an internal document developed to enhance ecological values if a company wants to go “beyond compliance.”

A plan may relate to a specific site or may incorporate multiple sites to achieve the best outcomes by utilizing all available tools. Such plans are also ideal for incorporating guidance from the MSRS, including principles covered in Section 3, and standard practices covered in Section 4.

Plans are often dynamic, allowing regulators and mining companies to refine and improve an environmental outcome, including adaptive management and the incorporation of new knowledge and techniques. A plan may also have commitments to offsets, science, publications, and other indirect outputs, and may address critical issues such as restoration scheduling, and managing legacy issues where previous restoration has underperformed.

**Mine Closure Plans.** MCPs cover all activities required before, during, and after the operating life of a mine to produce a landscape outcome agreed to by stakeholders. It can be a dynamic document that is regularly reviewed and refined over time to ensure that it reflects the current knowledge relevant to the development and rehabilitation status of the mine (World Bank Group 2021).

A closure plan includes:

- PMLU and stakeholder engagement.
- Closure outcomes, commitments, and implementation.
- Closure monitoring and management (including the role of adaptive management).

As MCPs are often the formal repository for updating regulators on progress toward mine closure, they provide the opportunity for mining companies to demonstrate their commitment to best practice. Within the MCP the MSRS can act as a framework to articulate how mining companies are delivering the best ecological restoration that can be achieved given the limitations at a site.

**Annual Environmental Report.** Annual environmental reports (AERs) are the typical mechanism for mining companies to demonstrate environmental compliance to the regulator. These reports document and provide the evidential basis for compliant

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mining and *restoration activities*, including progress toward achieving environmental outcomes and closure objectives for the site. Evidence in achieving compliance should include monitoring reports and data, which are sometimes lacking in high-level reports.

The MSRS can be useful in preparing AERs by including the Social Benefits and Ecological Recovery Wheels (Principles 1 and 6) to show progression toward the agreed completion standard. The AER reports are often publicly available and the Wheels can be effective communication tools between the mining company and stakeholders (Principle 1). By reporting on ecological performance through an AER, mining companies can demonstrate that they are operating under best practice, even if restoration is not meeting its goals due to unplanned circumstances.

### Adopting the MSRS into Company Policy

Adoption of the MSRS into company practice and policy can help mining companies build and maintain SLO, contribute to the SDGs and achieve corporate social and environmental objectives that leave a positive and enduring legacy long after mining has ceased. Importantly, early adoption of the MSRS into a mining operation can help reduce environmental, financial, and corporate risk in relation to achieving site relinquishment (LPSDP 2016c).

In the emerging world of "green credentials" for products and services, mining companies incorporating best practice ecological restoration into business models will help create market differentiation for their mineral products. Structuring the restoration process to align with the eight principles (Section 3), SoPs (Section 4) and the Social Benefits and Ecological Recovery Wheels ensures that the restorative approach is holistic and aspires to maximize restoration outcomes. The MSRS can also be used as a tool to align and communicate restoration expectations and outcomes to mining companies, regulators, and stakeholders. When implemented and utilized effectively, the MSRS will facilitate and enhance the establishment and strengthening of the trust model (Fig. 3).

The early adoption of the MSRS demonstrates to its stakeholders and employees a corporate culture and commitment to the environment. Increasingly, employees seek to be aligned with environmentally responsible business practices and adoption of environmental standards such as the MSRS can facilitate the attraction of staff as an employer of choice. A company that has policies that go beyond minimum regulatory compliance to fully engage in the highest level of ecological restoration practicable will promote a culture of business excellence.

## Section 3 — Eight Principles that Underpin the Ecological Restoration and Recovery of Mine Sites

Adapted from the International Standards (Gann et al. 2019),[15] other relevant leading documents, scientific literature, and *practitioner* experience, eight aspirational principles underpin the ecological restoration and recovery of mine sites. In combination, these principles provide a framework to define, guide, and measure the activities and outcomes of ecological restoration and other restorative practices in mining landscapes across the globe. The SDGs that relate to each of the principles, specifically in the context of mining, are indicated by icons at the start of each section. The eight ecological restoration principles for mine sites are to:

1. Engage stakeholders throughout the LoM.
2. Draw on many types of knowledge.
3. Be informed by reference ecosystems, while considering environmental change.
4. Support ecosystem recovery processes.
5. Assess against clear goals and objectives, using measurable indicators.
6. Seek the highest level of recovery attainable.
7. Gain cumulative value when applied at large scales.
8. Employ a continuum of restorative activities.

### Principle 1 — Engage Stakeholders Throughout the LoM.

1 NO POVERTY
3 GOOD HEALTH AND WELL-BEING
5 GENDER EQUALITY
8 DECENT WORK AND ECONOMIC GROWTH
10 REDUCED INEQUALITIES
11 SUSTAINABLE CITIES AND COMMUNITIES
16 PEACE, JUSTICE AND STRONG INSTITUTIONS
17 PARTNERSHIPS FOR THE GOALS

Mine site restoration projects need to provide active and genuine engagement opportunities with stakeholders throughout the LoM.

Stakeholders are integral to defining the vision, targets, goals, objectives, and methods of implementing and monitoring restoration projects that ensure equity and inclusiveness. In addition, identifying and understanding the impacts of a mine site through collaborative, informed, and consensual stakeholder consultation is the key to building dialogue and trust, both of which are vital to building and maintaining the SLO. This trust fosters respect for different viewpoints and knowledge systems and maintains interest and commitment during all phases of the project. For these reasons, managers of mine sites must identify and engage those with a genuine interest in the ecological, cultural, social, and natural capital values (including ecosystem services), that may be impacted by the mine over the long-term. Identification and engagement of these stakeholders should occur early in the mine planning process, before deciding a PMLU and setting ecological restoration goals. It should continue throughout exploration, feasibility, approvals, operations, decommissioning, restoration, and closure, incorporating, where appropriate, *participatory monitoring*.

Diverse and representative stakeholders are needed to accommodate and consider a wide variety of interests and opinions. The relevant stakeholders for a mining project may be wide-ranging including, but not limited to, combinations of the following: Indigenous peoples,[16] landowners, local and regional

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[15] Due to the large amount of content used throughout this section from Gann et al. (2019), it is generally not cited elsewhere in this section; other citations are supporting or additional. Each principle in the MSRS aligns with a comparable principle in the International Standards, which contains additional content that supplement the MSRS.

[16] In some countries, the term stakeholder should not be applied to Indigenous people because of their constitutionally protected rights and expectations to interact with governments on a nation to nation basis (Porter 2006).

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communities, civil society including nonprofits, government and regulators, business, investors, industry peers, academia, and media. Key affected stakeholders (e.g., landowners, Indigenous groups, government regulators, and local communities) should be directly involved in closure and restoration planning with broader stakeholders informed and updated on progress (ICMM 2019; Mansourian et al. 2019). When engagement is with Indigenous peoples, restoration programs should be co-designed, have ethics developed for cultural safety in the dialogue and include the concept of Free, Prior, and Informed Consent (FPIC) as recognized in the United Nations Declaration on the Rights of Indigenous Peoples (FAO 2006).[17] Mine developments that have commenced without appropriate stakeholder consultation should rectify this deficiency as early as possible so as not to jeopardize the long-term benefits of proposed restoration activities.

Importantly, stakeholder engagement should be respectful of local traditions, customs, and social expectations which, from a mine development perspective, may change over the LoM. Thus, mining companies and regulators should acknowledge that the SLO built at the beginning of the project may not reflect the SLO perceived by communities at the end of the LoM, requiring flexibility and responsiveness in mine planning due to changed social values. Time and resources must be allocated to culturally appropriate processes that build trust, particularly with Indigenous and local communities. Such a collaboration can lead to more rapid and effective local decision-making, particularly when participatory or collaborative approaches are implemented. Collaboration also promotes equitable sharing of cultural, social, and environmental benefits derived from projects.

When ecological restoration of a local native ecosystem is the aim, it is important to recognize that restoration may yield multiple benefits that are important to stakeholders beyond the direct recovery of biodiversity and ecosystem functions, including personal, cultural, and socialeconomic values. For example, communities located within or near mine sites may experience improved health and other benefits from restoration that enhances the quality of air, land, water, and habitats for native species, the repair of damaged ecosystems, and the reconnection of society with nature (Robinson & Breed 2019; Breed et al. 2020). Indigenous peoples and local communities (both rural and urban) benefit where restoration reinforces traditional cultures, customary practices, and livelihoods (e.g., subsistence fishing, hunting, and gathering; Box 3). Furthermore, restoration can provide short-term and long-term employment opportunities for local communities, creating positive ecological, economic, and social feedback loops that can extend well beyond the LoM. See Urzedo (2022) in Appendix S2c for further discussion on Indigenous rights and contestations in mining contexts.

### Box 3 Post-mining ecological restoration to support cultural reindeer grazing.

The Kiruna Mine is operated by Luossavaara-Kiirunavaara Aktiebolag (LKAB), a government-owned Swedish mining company. It is an operating underground iron ore mine, with ore processing plants, in the arctic region of northern Sweden. The mine is located within the territory of two Indigenous Sami villages that have reindeer husbandry rights. The mine is still operating with limited current opportunities for ecological restoration. Nevertheless, advanced planning and trials are being completed to develop the tools and technologies for large-scale restoration once areas become available. The ecological restoration project aims to restore the same ecosystems that once covered the land: mountain heath, mountain birch forests, pine heath forests, peat wetlands, cliffs, and scree slopes and thereby create grazing land for reindeer herding and values for biodiversity. Consultation and engagement with the Sami villages were included throughout the restoration design process through meetings and field visits. The first meeting provided information on the project goals and timeline. Follow-up meetings included a first draft for the design of the restored landscape with input from the Sami villages on proposed changes, and field visits with representatives from both villages to investigate desired landforms and species composition for good reindeer grazing. The Sami villages provided input to subsequent drafts of the design until agreed upon. Stakeholder engagement with Sami villages will continue throughout restoration implementation and monitoring. The full case study for the Kiruna mine is included as Appendix S1a.

Social and human well-being goals, including those that reinstate or reinforce ecosystem services, must be identified alongside ecological goals during the planning stage of a restoration project (see Principles 5 and 7, and Kragt (2022) in Appendix S2d for a discussion on the economic, social, and environmental value of restoration). Guidance for identifying appropriate goals to improve both social and environmental outcomes in *social-ecological systems* is provided in a range of documents (Burns & Church 2018; Mancini & Sala 2018; ICMM 2019; Young et al. 2019). A tool for evaluating progress toward social goals is provided in Table 2 and Figure 4. These templates can be adapted to suit the specific social goals of any project. Managing engagement with stakeholders regarding ecological restoration practices in mining, whether through consultation or on the ground actions, can be complex. Guidance documents are available to support stakeholder engagement efforts including, for example, ICMM's community development toolkit (ICMM 2012). This toolkit includes background, examples, and processes to coordinate relationships, planning, assessment, management, and monitoring and evaluation throughout the LoM.

Effective and responsive stakeholder engagement throughout the LoM reinforces the role of governance and enables ownership by the local community over social investment programs in the long term (ICMM 2019). Youth and women, particularly in impoverished communities, when fully engaged and

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[17] See also International Finance Corporation (IFC) Environmental and Sustainability Standard 7.

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**Table 2.** Sample social-benefits Five-star System for evaluating progress toward social goals in a restoration project or program. Social goals may be many and varied. Not all elements in this table will be relevant to all projects. The Social Benefits Wheel can be applied to small- or large-scale projects, with scale used as a multiplier of outcomes, rather than being itself an attribute (adapted from Gann et al. 2019).

| *Attribute* | ★ | ★★ | ★★★ | ★★★★ | ★★★★★ |
|---|---|---|---|---|---|
| Stakeholder engagement | Diverse, and representative stakeholders identified and made aware of project and its social and environmental impacts. Ongoing communication strategy prepared. | Key stakeholders supportive and involved in project planning phase. | Number and diversity of stakeholders, support, and involvement increasing at start of implementation phase. | Number and diversity of stakeholders, support, and involvement consolidating throughout implementation phase. | Number and diversity of stakeholders, support, and involvement optimal, and self-management and arrangements for site management continuity are in place. |
| Benefits distribution | Benefits to local communities negotiated, ensuring equitable distribution and reinforcement of traditional cultural relationships to the site. | Benefits to local communities starting and equitable distribution maintained. Traditional cultural elements integrated, as appropriate, into project planning. | Benefits to locals at an intermediate-level and equitable and intergenerational distribution maintained. Any traditional cultural elements well secured within project implementation. | Benefits to locals at a high-level and equitable and intergenerational distribution maintained. Substantial integration of any traditional cultural elements, increasing reconciliation prospects. | Benefits to locals and equitable and intergenerational distribution very high, with optimal integration of any traditional cultural elements, substantially contributing to reconciliation and social justice. |
| Knowledge enrichment | A diversity of relevant sources of existing knowledge identified and mechanisms for generating new knowledge selected. | A diversity of relevant sources of existing knowledge (and potential for new knowledge) informing project planning and monitoring design. | Implementation phase making use of many types of relevant knowledge, stakeholder feedback, and early project results. | Implementation enriched by many types of relevant knowledge as well as from trial and error arising from the project itself. Results analyzed and reported. | Implementation enriched by many types of relevant knowledge and results from the project disseminated widely including to others with similar projects. |
| Natural capital | Land and water management systems to reduce overharvesting and restore and conserve natural capital being put in place on site. | Land and water management systems resulting in low-level recovery and conservation of natural capital of the site. | Land and water management systems resulting in intermediate-level recovery and conservation of natural capital (including improved carbon and biodiversity budget). | Land and water management systems resulting in high-level recovery and conservation of natural capital (including carbon and biodiversity neutral status). | Land and water management systems resulting in very high level of recovery and conservation of natural capital (including carbon and biodiversity positive status). |
| Sustainable economies | Sustainable business and employment models (applicable to the project or ancillary businesses) planned. | Sustainable business and employment models commenced. | Sustainable business and employment models evaluated and adaptively managed for longevity post-closure. | Trials of sustainable business and employment models showing success supported by evidence of longevity. | Sustainable business and employment models with strong levels of success supported by evidence of longevity. |
| Community well-being | Core participants identifying as stewards and likely improving social bonding and sense of place. | All participants identifying and likely benefiting from improved social bonding and sense of place. | Many stakeholders likely benefiting from improved social bonding, sense of place, and return of ecosystem services including recreation. | Most stakeholders likely benefiting from increased social bonding, sense of place, and return of ecosystem services including recreation. | Community identification of the site as having wellbeing benefits and return of ecosystem services including recreation or other cultural values. |

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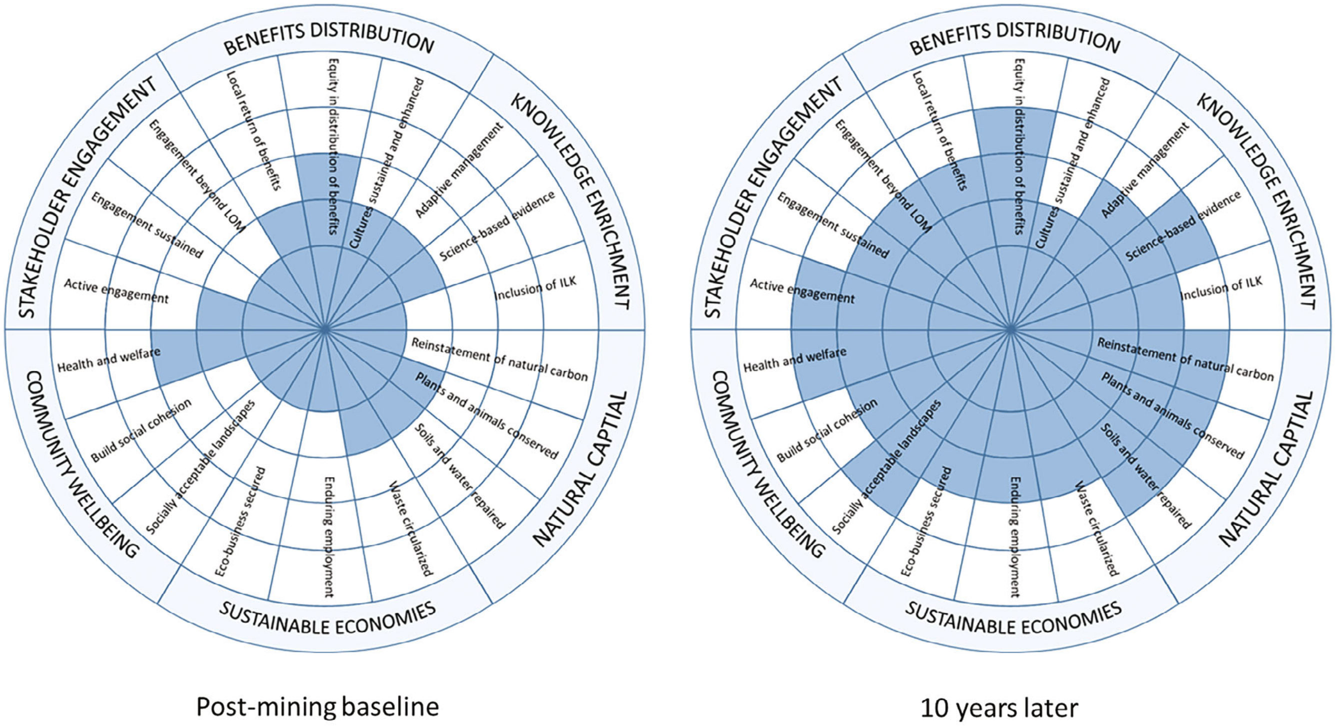

Post-mining baseline

10 years later

Figure 4. Example of *Social Benefits Wheels* to assist in tracking the degree to which an ecological restoration project or program attains social development targets and goals. In this hypothetical example, the left-hand wheel represents the condition of indicators for each of the six attributes before initiation of restoration actions; and the right-hand wheel depicts degree of social recovery for each indicator 10 years after initiating restoration actions. The social wheel and Table 2 can be customized to suit the specific goals of any ecological restoration project or program. It complements the Ecological Recovery Wheel used to evaluate ecological recovery progress compared to the project's reference model, which is introduced in Principle 6. For symmetry of design, six attributes and three subattributes are used in this example, but there may be more or fewer needed depending on the local context of a project (adopted from Gann et al. 2019).

empowered, can become important ambassadors. Such community engagement can bring improved equity, social justice, and human ecology components to a project (Urzedo et al. 2020). These are important underpinnings of the SLO and can help facilitate social support for the project.

To prepare for successful closure and relinquishment,[18] proactive planning and management for social transition at restoration sites is key to minimizing negative impacts, capturing benefits, and reducing legacy issues such as underperforming restoration outcomes. Host communities that have developed economic dependencies on mining operations will experience considerable socioeconomic disadvantage at closure. This can be especially true for those in remote areas, Indigenous communities, or in developing countries where the mine may be a primary local economic driver. The mine owner may be in a de facto socioeconomic leadership role that would otherwise be the responsibility of the government (ICMM 2019). Though it is challenging to define the boundaries of a mining company's responsibility for socioeconomic development, investment in social transition can result in sustainable and resilient community outcomes when government and stakeholders share in the decision-making, responsibility, and process of closure (ICMM 2019).

A significant and common challenge faced by the mining industry is to reinstate or improve relationships with stakeholders and the community for current or historical projects where the foundations for strong and considered engagement was not appropriately integrated into LoM planning. In these circumstances, establishing the "trust model" (Section 2) can be a long and difficult process, especially if trust has been specifically violated in past actions.

### Principle 2 — Draw on Many Types of Knowledge.

The practice of ecological restoration at mine sites requires a high degree of ecological knowledge that is drawn from formal training, industry and practitioner experience, ILK,[19] and critically, is informed by the best available evidence-based science. Knowledge is the product of observation, experimentation, and well-documented adaptive management. The best available knowledge should inform the design and implementation of post-mining

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[18] Relinquishment may not necessarily mean full transfer of all liabilities for a site post-mining. Monitoring of key risk areas (e.g., tailings facilities) may remain the responsibility of the mining company.

[19] ILK includes both the concepts of *Traditional Ecological Knowledge* and *Local Ecological Knowledge*.

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ecological restoration and drive a culture of continual improvement (see Principle 5). Regulatory requirements of native ecosystem PMLUs require that mining companies predict outcomes of ecological restoration with a reasonable degree of certainty[20] and have accompanying procedures, monitoring programs, and financial resources in place to undertake corrective interventions and adaptive management. All types of knowledge and associated monitoring must be incorporated prior to and throughout the LoM to contribute toward a "restorative culture" (Blignaut & Aronson 2020). Delayed investment in high-quality and locally relevant knowledge during restoration planning may lead to substantial risk in the relinquishment phase of a mine (LPSDP 2016c).

*Scientific knowledge.* Industry investment in research fosters innovation that helps meet the unique challenges of ecological restoration and recovery at mine sites. Sound science is essential for the cost-effective application of restoration, Restoration planning needs to draw upon the knowledge of subject experts while acknowledging unique environmental and biological aspects of individual mine sites (Box 4). Research is often undertaken to react to an immediate problem. However, real value and change can result when a strategic, whole-of-project perspective is adopted. If instigated early in the mining process and continued through the life-of-mine such research has the potential to provide solutions to issues as they arise. Innovation between the mining sector and research partners can improve environmental and social outcomes (Young et al. 2019; Rosa et al. 2020), especially when industry forms focused, long-term relationships with relevant experts (Fig. 6) (Erickson et al. 2016; Stevens et al. 2016). Early scientific engagement can de-risk mine restoration and engender confidence with mine environmental staff when the science engagement is adaptive and focused on resolving impediments to recovery and closing the recovery gap (Fig. 7) while acknowledging that unique solutions might be required to address particular site-specific issues.

Mine site restoration knowledge may also have a high value for reinstating ecological functions and ecosystem services in *other* degraded or highly modified landscapes (e.g., degraded agricultural systems, urban areas). Mining companies that adopt a proactive and positive attitude to restoration at all levels of management, and actively seek to continue to improve restoration performance through science, benefit both internally and externally with partnerships extending to local communities, civil society, non-government and government organizations (Box 5).

*Indigenous and local knowledge.* ILK custodians, including restoration practitioners, often have extensive, deep-time, and detailed information about sites, cultural assets, and native ecosystems drawn from long-term relationships and shared community knowledge. The co-design and appropriate inclusion of ILK custodians improves ecological, social, and cultural outcomes from restoration and helps guide social transition programs and the development of culturally appropriate restoration targets and goals. For ecological restoration to be successful, it is built upon the narratives of the local people including livelihood expectations (Schmidt et al. 2019; Hill et al. 2020). Useful guidance on how to incorporate ILK and other knowledge systems into conservation and restoration planning includes The Intergovernmental Platform on Biodiversity and Ecosystems Services[22] (IPBES) guidance and, "Our Knowledge, Our Way" provides Indigenous-led approaches to strengthening and sharing Indigenous knowledge through an Australian Indigenous lens (Woodward et al. 2020).

*Practitioner knowledge.* Practitioner knowledge arises through on-the-ground experience in restoring ecosystems, often in conjunction with information sourced from a variety of scientific and technical disciplines. Practitioners can be a rich source of locally relevant knowledge to restoration ecology, including soil properties, plant reproductive systems, wildlife, invasive species, and natural disturbance regimes. ILK custodians can also be restoration practitioners through delivery of restoration products and services to mines. The respectful and formally recognized sharing of practitioner knowledge has the capacity to greatly improve decision-making, deliver time- and cost-efficiencies and build trust bonds between mining and local communities.

### Box 4 Targeted research resulting in improved ecological outcomes

Heap leach processing for gold began in 1985 at the Summitville Mine (Colorado, U.S.A.) and in 1991 the state of Colorado ordered closure due to pollution of regional surface waters. By 1994, the site was abandoned and declared a Superfund Site[21] by the U.S. Environmental Protection Agency. In 1995, restoration on 200 ha of highly disturbed land commenced. The short-term goal was to stabilize soils and prevent off-site migration of metal-laden sediments. The longer-term goal was to move the site onto a trajectory toward reference conditions.

A greenhouse experiment screened 36 potential technosols, with subsequent field experiments to test the most promising treatments. From 1999 to 2001, the site was re-contoured, amended with the most promising technosol, and seeded. Monitoring at the site documented an increase in uniformity of vegetation cover, an increase in native species richness, and a significant shift toward reference conditions (Fig. 5). The full case study for the Summitville gold mine is included as Appendix S1b.

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[20] There is always a level of uncertainty when undertaking restorative activities, including ecological restoration.

[21] Superfund sites are polluted locations in the United States requiring a long-term response to clean up hazardous material contaminations (Wikipedia 2021).

[22] https://ipbes.net/indigenous-local-knowledge

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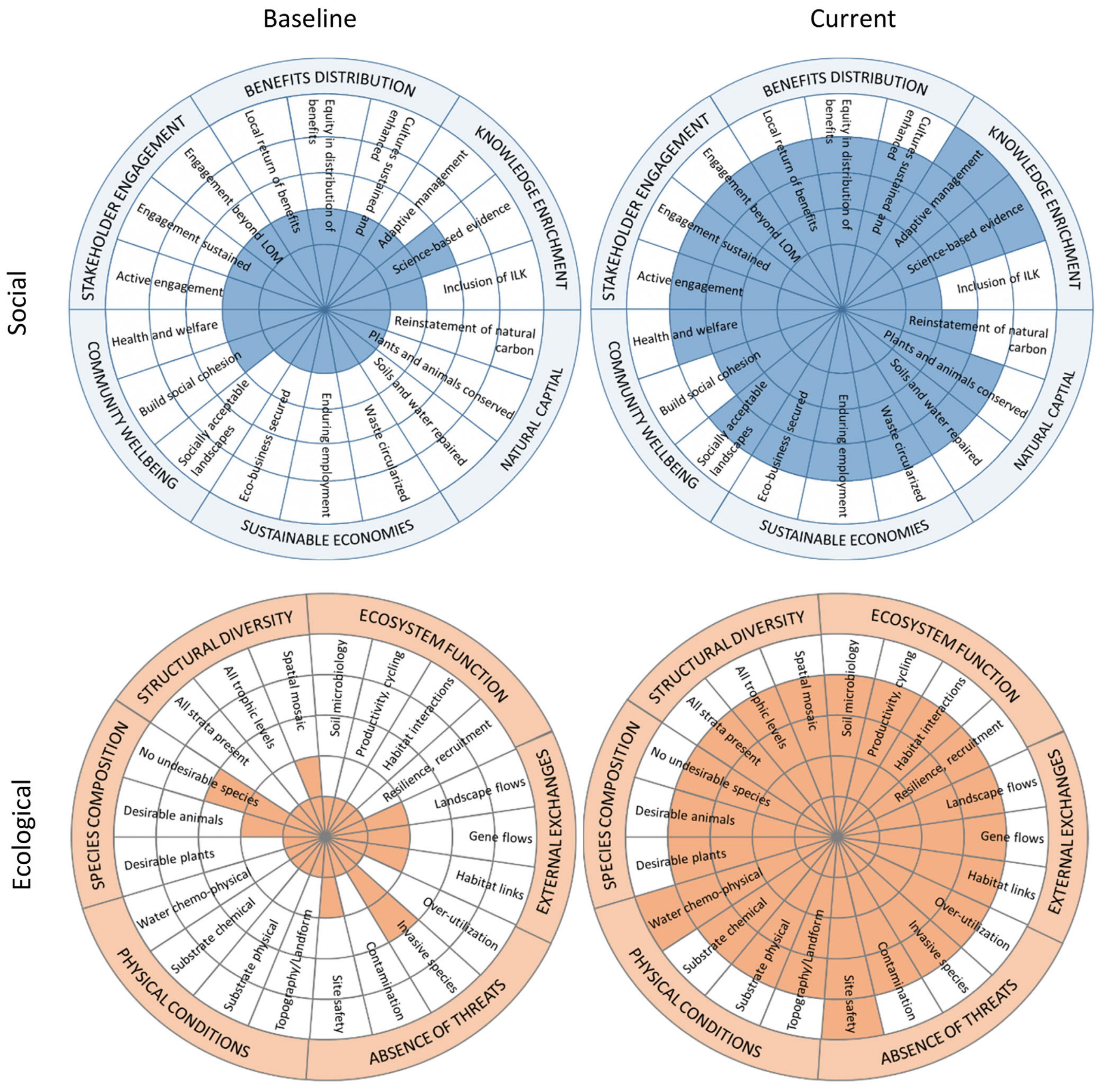

Figure 5. Summitville gold mine, Colorado, USA, Social Benefits and Ecological Recovery Wheels assessed at post-mining baseline and current conditions. The Ecological Recovery Wheel has been updated to assess ecological restoration after mining. See Principle 1 for more detail on the Social Benefits Wheel and Principle 6 for more detail on the Ecological Recovery Wheel.

*Knowledge sharing.* An important approach to advance the science and practice of mine site restoration is to develop and promote information sharing within the industry, particularly among and between multinational mining companies, and among countries where similar mining impacts occur. *South–South*, *North–South*, and *Triangular* Cooperation can provide platforms to enable knowledge sharing (Liu et al. 2017). Experience and expertise sharing, co-financing, and co-development of new knowledge for more effective policies and practices should be encouraged among mining companies, countries, and regions. Although some industry knowledge will necessarily remain proprietary, incentives should be developed to promote knowledge sharing as related to restoration. The sharing of restoration knowledge within and across the mining community would reduce risk, minimize cost, increase restorative certainty, and ultimately improve ecological and social outcomes. Mechanisms such as a co-investment science fund where data and results are shared can facilitate rapid learning at the industry scale.

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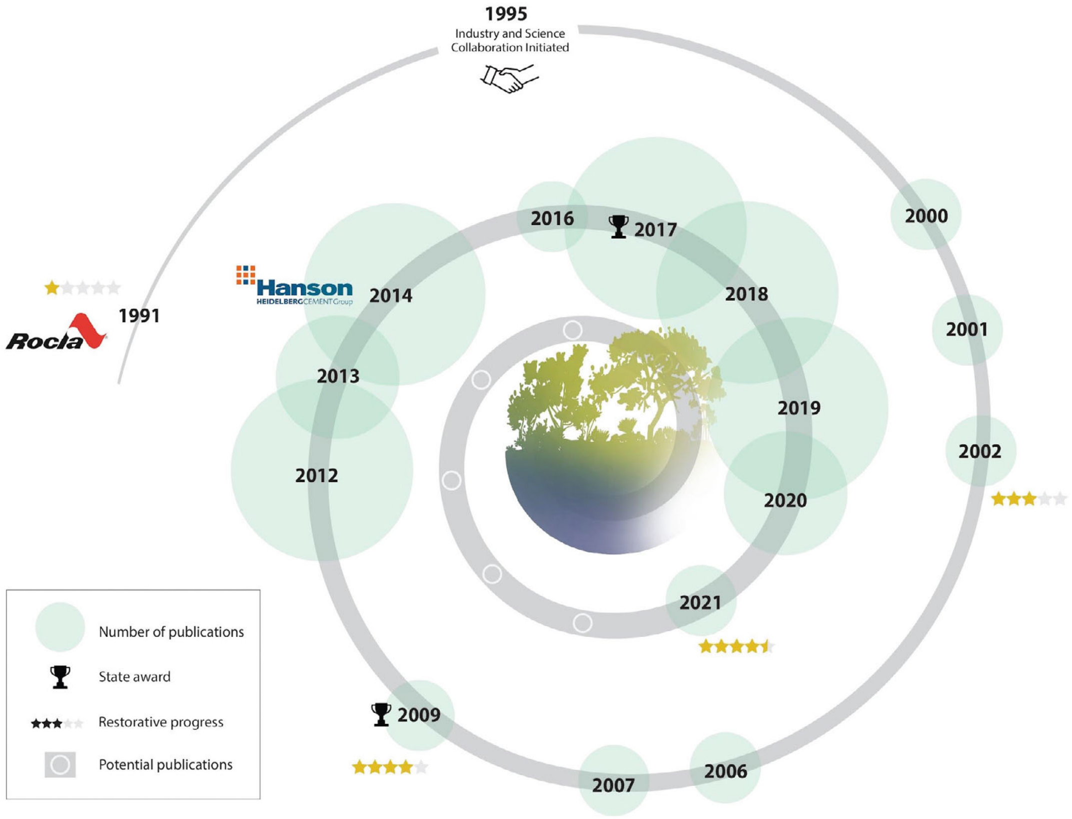

Figure 6. *Knowledge building and improved restoration outcomes* for a sand quarry showing progression toward achieving a fully recovered ecosystem similar to the reference model (courtesy of Hanson Construction Materials).

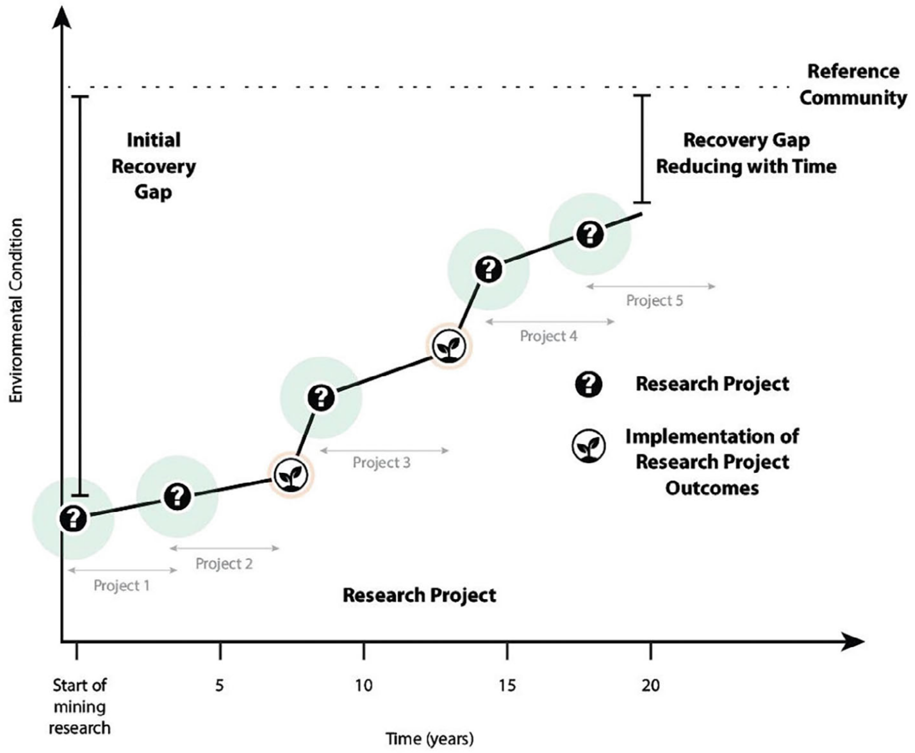

Figure 7. *Ecological restoration performance and corporate knowledge* as it relates to investment and relationships with science.

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### Box 5 Learning through industry-researcher partnerships.

Banksia woodlands are a Threatened Ecological Community (TEC) that overlay important sand resources in the Perth region of the Southwest Australian Biodiversity Hotspot. These woodlands are biodiverse, with a high number of endemic species. Prior to mining, commencing in the 1990s there was little understanding of how to restore these biodiverse native ecosystems. As a result, Hanson Construction Materials realized early in their mine development that restoration to the highest standard would be fundamental to maintaining their social and regulatory license to operate.

The company invested in more than 20 years of cross-disciplinary research with key research partners to solve what were major impediments to reinstate a functional and biodiverse woodland ecosystem. Hanson has, and continues, to support research that target impediments for improving outcomes such as understanding and optimization of the regenerative potential of the soil seed bank, improving methods for topsoil handling and storage, developing innovative seed germination enhancement pre-treatments (e.g., smoke), enhancing nursery production methods and outplanting treatments (e.g., tree-guards, antitranspirants), investigating ecophysiological parameters (nutrient and soil water relations) for improved seedling survival and testing site treatments (e.g., mulching, irrigation and soil ripping practices, and application of soil stabilizers). Hanson continue to enrich their knowledge base by continuing to support postgraduate research with on-site educational tours for community and visiting expert groups. The company is an active supporter of national and international conferences while fostering international linkages and partnerships with other mining sectors. This has led to increasing performance across almost all attributes in the Social Benefits and Ecological Recovery Wheels (Fig. 8) and as a result, Hanson is a trusted and respected mining company that routinely achieves one of the highest restoration outcomes in mining in Australia. The full case study for the Hanson sand quarry is included as Appendix S1c.

It is important that capable and appropriately skilled/trained environmental teams are assembled that promote a shared learning environment, learning within- and cross-sector (e.g., agriculture, soil sciences, seed technologies), and staff are offered formal training in ecological restoration and processes to enable best practice to be understood and deployed at sites. This can include innovations and incentives such as SER's practitioner certification program.[23] All knowledge, practice, and experiences generated through restoration practice should be documented, stored appropriately, curated, and easily accessible to ensure knowledge transfer to future employees, project collaborators, and appropriate stakeholders.

### Principle 3 — Be Informed by Appropriate Reference Ecosystems, while Considering Environmental Change.

6 CLEAN WATER AND SANITATION 14 LIFE BELOW WATER 13 CLIMATE ACTION 15 LIFE ON LAND

When mining occurs in native ecosystems,[24] ecological restoration requires identifying the target native reference to be restored and developing reference models for planning and communicating a shared vision of project goals. Where possible, reference models should be based on specific real-world ecosystems (e.g., peat bog, tropical forest, desert shrubland, savanna, wetland) that are the targets of the restoration activities. Optimally, the reference model describes the approximate condition the site would be in had mining not occurred accounting for the inherent capacity of ecosystems to change in response to changing background conditions (e.g., climate change). For mine sites operating across ecosystem mosaics with alternative stable states (e.g., mixed grassland, woodland, forest landscapes), it may not be possible to know exactly what ecosystem state the mine site would be in, yielding more than one potential target ecosystem. In these cases, technological, biological, or social considerations may influence the choice of ecosystem to be restored.

In other circumstances, where the existing or immediate prior ecosystem may be already transformed (e.g., farmland) or highly degraded, the PMLU may offer an opportunity to restore a native ecosystem similar to what may exist had the preceding disturbance not occurred, thus achieving net gain for nature. In these scenarios support for this transition to a native ecosystem should be confirmed through stakeholder engagement.

The impacts of substantial and often intractable environmental changes caused by extraction as well as production wastes may require consideration of adjusted or alternative reference models (Fig. 9) to guide restoration after mining. For instance, project managers may adopt alternative reference ecosystems if it is shown (by research or documented evidence) that it is not possible or technically feasible to restore the native ecosystem that would exist at the site if mining had not occurred.[25] Cost, a lack of time (due to impending closure and relinquishment), or insufficient research are not appropriate reasons to avoid the use of a local native reference ecosystem when intact native ecosystems have been or will be impacted by mining. However, the selection of alternative reference ecosystems may be valid due to irreparable changes in geological stability or structure, soil profile, hydrology, and nutrient availability. Deciding when an alternative reference ecosystem is appropriate is dependent on local conditions and demonstrated

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[23] SER operates a system to certify practice-based and formal learning in restoration through its Certified Ecological Practitioner (CERP) and Certified Ecological Restoration in Training (CERPIT) programs.

[24] Native ecosystems can include traditional cultural ecosystems or semi-natural areas in some scenarios. If native ecosystems are impacted by mining, they should be restored to the extent practicable regardless of the amount of degradation pre-mining.

[25] Implicit is the requirement that stakeholder agreement has been obtained for adjusting the nature and composition of the ecosystem to be restored.

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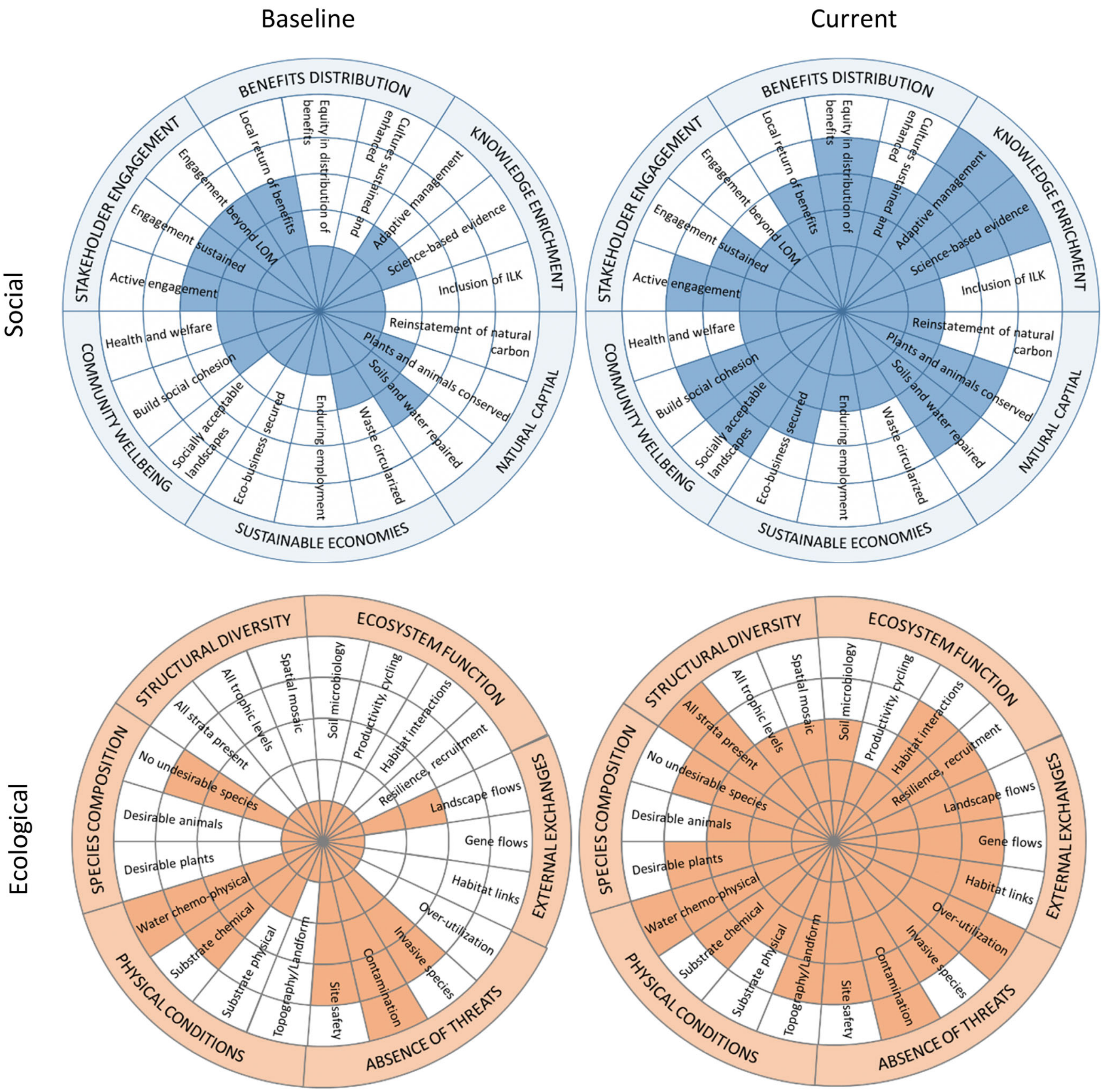

Figure 8. Hanson sand quarry, Perth Australia, Social Benefits and Ecological Recovery Wheels assessed at post-mining baseline and current conditions.

irreversibility, which will require skilled and informed ecological judgment. In many cases where restoration was assumed to be impossible following mining, recovery was achieved after the application of innovative approaches by experienced restoration teams (e.g., the discovery of smoke-stimulated germination in mine site restoration by Roche et al. 1997 transformed the capacity of mining companies to restore a more complete plant species inventory in Australia). Where potential for recovery is in doubt, but recovery is highly desirable, a standard approach is to conduct trial treatments on a small area for a sufficient period (e.g., employing Principle 6 below) to determine efficacy, applicability, and to contribute to cost efficiency. Trial treatments are best designed as collaborations between scientists and restoration practitioners based on key uncertainties and predicted effects, rather than employing a random approach of trial and error, rationalized by the idea that future directions can be changed if a project fails. Effectively designed trial treatments can determine whether changes caused by mining are feasible

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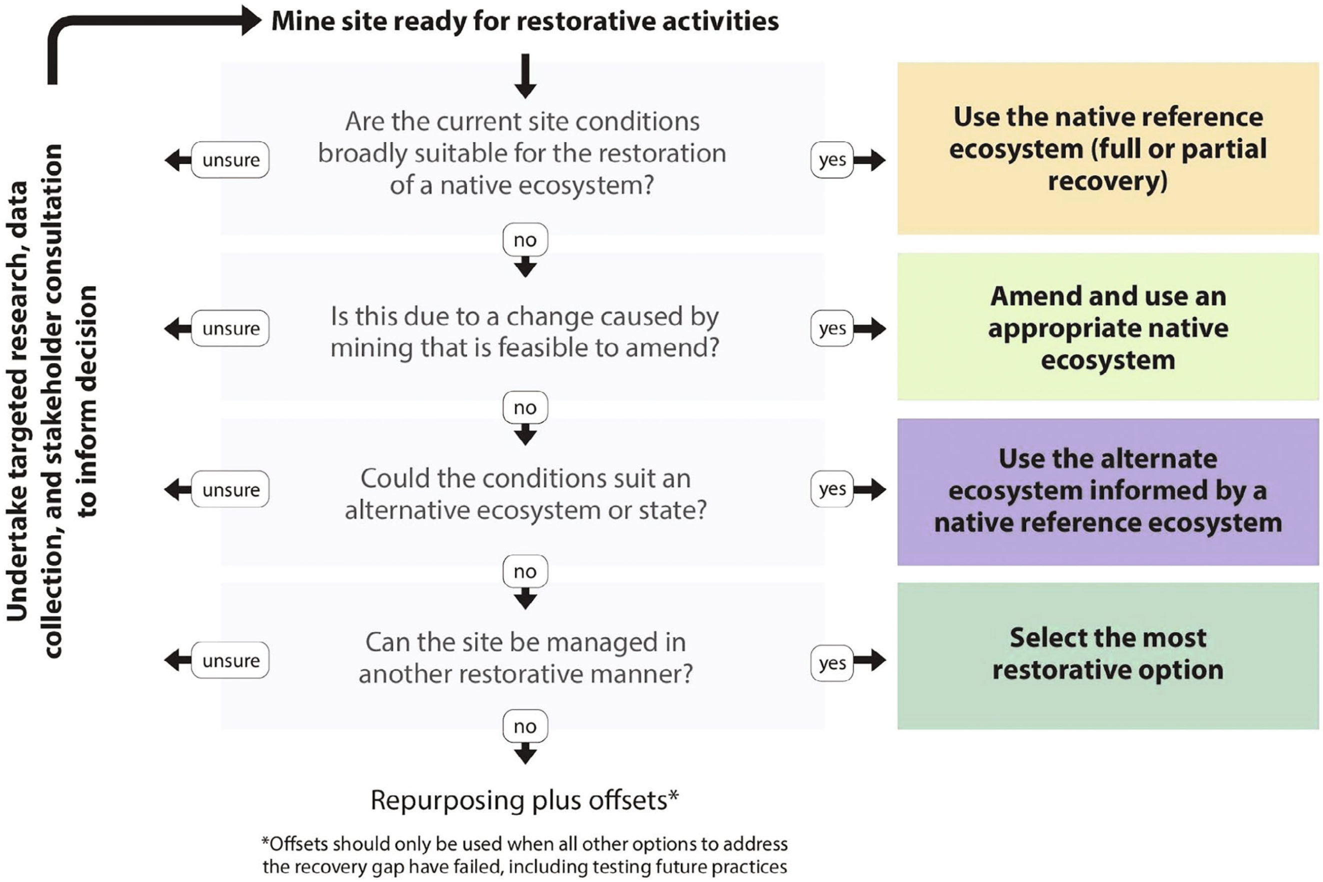

Figure 9. Simplified *decision tree to assist selection of appropriate reference ecosystems or other PMLU options* for restorative projects (adapted from Gann et al. 2019). Where a restorative option is not possible onsite, repurposing may be considered in combination with restoration in an alternative location.

to be amended, thus allowing for the choice of a restorative option. In other cases, onsite repurposing may be the best option, with restoration taking place in an alternate location (Box 6).

Once target reference ecosystems are selected, best practice is to build reference models based on multiple sources of information on the specific ecosystem attributes to be restored. These sources include multiple existing analogs or reference sites (sites

### Box 6 A policy framework for ecological offsets.[26]

Offsets[27] are measures and actions that attempt to compensate for planned losses in habitat, species, or ecological functions that are broadly applied across terrestrial, aquatic, and marine habitats. Offsets are recommended only after the first three stages of the Mitigation Hierarchy as it pertains to native ecosystems and biodiversity (see Fig. 1) have been thoroughly examined and exhausted: *avoidance*, *minimization*, *restoration* or *rehabilitation*.

There are major inconsistencies in offsetting policies and practices, and recent reviews (Samuel 2020) highlight that offsets rarely achieve the required ecological compensatory outcome to result in a net gain for the environment. Even in jurisdictions with strong environmental laws, averting loss using biodiversity offsets failed to deliver benefits by an order of five times, with offsets unable to show an effective improvement in biological status (Maron et al. 2015) and consistently failing to consider multiple ecological, regulatory, and ethical losses within the “no-net-loss” objective (Moreno-Mateos et al. 2015).

*Continued*

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[26] Box 6 was written by Prof. Kingsley Dixon (Curtin University), Tein McDonald (Society for Ecological Restoration Australasia), David Keith (University of New South Wales) and George Gann (Society for Ecological Restoration). A full discussion on the topic is provided in Appendix S2e.

[27] Gann et al. (2019) state that ecological restoration should not be invoked as a reason for the destruction of native ecosystems particularly following mining where restoration offsets rarely achieve “like-for-like” and net-gain outcomes for native ecosystems including old growth forest ecosystems.

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## Box 6 A policy framework for ecological offsets.[26]—cont'd

In cases where mining companies use biodiverse plantings as a mechanism for carbon emission offsets, ecological restoration should be engaged as best practice abatement methodology to maximize net gain opportunities. Engaging and embedding the International Standards (Gann et al. 2019) in this practice will reduce the risk of establishing systems that fail to return ecosystem functionality. In these circumstances it is particularly important to plan for and implement the very highest recovery interventions possible as these sites can get "locked-up" in permanency clauses (particularly where carbon mitigation might require decadal or longer periods of uninterrupted growth), which could prevent additional additive restorative actions from occurring onsite.

### Model Policy Framework

To facilitate effective offset practice in mining restoration:

1. Offsets should be framed within an agreed national biodiversity offset framework that includes consistent principles and standards that provide *net gain* in biological and ecological values.
2. Where offsets include ecological restoration, appropriate standards are applied based on the International Standards (Gann et al. 2019) or these MSRS to guide planning, implementation, monitoring, and review practices noting that restoration should not be invoked as a reason for the destruction of nature.
3. Offsetting methodologies including ecological restoration should be based on principles of continuous improvement that include commitment to adaptive research and adaptive management.
4. Offset proposals must be independently peer-reviewed by restoration specialists and ecological subject experts with relevant knowledge and understanding of the appropriateness, feasibility, and risks associated with an intended offset to compensate for the mining impact.
5. Offsets must provide a "like-for-like" outcome for biodiversity and ecosystem values and function that achieve a proven net gain[28] outcome for biodiversity that is near to or matched to the mining impact area including ecological processes and functional attributes.
6. Proponents demonstrate success in achieving competent ecological restoration based on approved completion criteria.
7. Appropriate monitoring standards are adopted and implemented and where an offset deviates from the agreed trajectory, mitigation, and proven corrective actions are implemented.

See Dixon et al. (2022) in Appendix S2e "Mitigation Hierarchy and ecological offsets" for a more complete treatment of offsets policy and implications.

that are environmentally and ecologically similar to the project site, and, optimally, have experienced little or minimal degradation) and information collected during the *pre-mining baseline* inventory.[29] For reference models to adequately capture inherent variation in ecosystem attributes, they should be developed based on an adequate number of reference sites. Where an adequate number of sites are not available, it may be necessary to utilize information from sites impacted by degradation (e.g., grazing, inappropriate fire regimes, invasive species), but with an understanding of how these impacts have affected and altered the sites, and therefore how that may also alter the final development of the reference model.

In developing a reference model, six *key ecosystem attributes* (Table 3) are used to account for ecological complexity, temporal change (i.e. the successional or equilibrium dynamics of the ecosystem) and *resilience*. Although all six attributes should be included in the reference models, given the large range of ecosystem types for which ecological restoration is needed following mining, the specific *indicators* measured for each attribute will vary across ecosystem types and projects.

Reference models are not intended to immobilize an ecosystem at a specific point in time but should reflect natural processes, and succession. An inherent property of ecosystems is that they change over time because of internal (e.g., changes in population growth rates) and external (e.g., physical disturbances, climate change) factors. Reference models should be developed with an explicit understanding of temporal dynamics to develop feasible and relevant, restoration designs that allow local species to recover, adapt, evolve, and reassemble. See Cui and Lui (2022) in Appendix S2i for further discussion on the implications of climate change for the ecological restoration of mine sites.

Multiple reference models, with differing spatial and temporal considerations, may be needed for a single mine site restoration project. First, large project sites or those with varied topography are likely to have included a mosaic of ecosystems and their ecotones. Second, in successional landscapes or those where *natural regeneration* is an appropriate approach for restoration, sequential references may be needed to reflect ecosystem dynamics or anticipated changes over

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[28] Offset activities such as land acquisition and conservation set-asides alone do not create net gain, but contribute to ecological losses unless they are accompanied by genuine restoration actions that recover commensurate biodiversity and ecosystem values.

[29] Pre-mining baseline inventories inform the reference model and allow assessment of progress towards full or partial recovery. Post-mining baselines allow assessment of progress after the achievement of safe, stable, and non-polluting conditions at the site. Baseline inventories record biotic and abiotic elements at the site, including its compositional, structural, and functional attributes, as well as external threats and positive external exchanges.

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**Table 3.** Description of the key ecosystem attributes used to characterize the reference ecosystem, as well as to evaluate pre- and post-mining baseline condition, set project goals, and monitor degree of recovery at a restoration site. These attributes are suited to monitoring in Principle 5 and the Five-star System discussed in Principle 6 (adapted from Gann et al. 2019; Standards Reference Group SERA 2021).

| *Attribute* | *Description* |
|---|---|
| Absence of threats | Direct degradation drivers (e.g., *over-utilization*, active contamination, sources of invasive species, eroding land-surfaces) are minimal or effectively absent. |
| Physical conditions | Environmental conditions (including the physical and chemical conditions of soil, water, and topography) required to sustain the ecosystem are present. |
| Species composition | Species characteristic of the ecosystem are present, whereas undesirable species are minimal or effectively absent. |
| Structural diversity | Appropriate diversity of key structural components, including demographic stages, faunal *trophic levels*, vegetation *strata* (including nesting and denning habitat), and spatial heterogeneity are present. |
| Ecosystem function | Appropriate levels of growth and productivity, nutrient *cycling*, decomposition, habitat, species interactions, and types and rates of natural disturbance are present. |
| External exchanges | The ecosystem is appropriately integrated into its larger landscape and watershed context through positive abiotic and biotic flows and exchanges. |

time[30,31] Third, for ecosystems with complex equilibrium dynamics, multiple successional pathways may exist, and multiple models may be necessary to attempt to describe different possible alternative states or restoration outcomes. Fourth, across a site there may be varying types and levels of degradation and potential for restoration, and hence the need to select different reference ecosystems (Fig. 9), with distinct reference models for each. Once developed, the reference model is used to inform the restoration targets, as described in the goals and objectives (Principle 5). See Gann et al. (2019), section 4, part 1, for more complete treatments of reference ecosystems.

## Principle 4 — Support Ecosystem Recovery Processes.

6 CLEAN WATER AND SANITATION 13 CLIMATE ACTION 14 LIFE BELOW WATER 15 LIFE ON LAND

The most reliable and cost-effective way to kick-start restoration is to harness the potential of remnant biota (e.g., soil microbiome, plants, animals) to regenerate (i.e. to colonize or expand from in situ components). This is often accomplished at mine sites via appropriately collected and stored topsoil noting that topsoil can rapidly lose its biological integrity when stripped or stored inappropriately. Due to the destructive nature of mining, restoration at mine sites requires substantial intervention to compensate for the loss of *natural recovery potential*. Both the geographical region and the specific extraction process can have a significant impact on the level of intervention required to reach a state where the site can support natural ecosystem recovery processes. An assessment is needed early in the planning process to determine: (1) potential for regeneration after the cessation of mining and (2) need to intervene to reinstate missing *abiotic* and biotic elements. This assessment should be informed by the type of mining proposed and knowledge of the *functional traits* (particularly recovery mechanisms) of individual species likely to occur as *propagules* (sources of plants and animals) on site or available to colonize the site from adjacent areas. Where knowledge gaps exist, tests of the recovery response in smaller areas are essential prior to large-scale implementation. Restoration activities, therefore, should focus on reinstating components and conditions suitable for natural processes to recommence and support recovery of ecosystem attributes, including capacity for self-organization and for resilience to future stresses, which is often a key requirement that mining companies need to demonstrate in order to meet agreed closure and relinquishment objectives. This is particularly important for reinstating ecosystems that may require long periods (decades to centuries) to achieve ecological stability and provide the full suite of ecosystem services to support biodiverse outcomes (Moreno-Mateos et al. 2017). Restoration should be planned, implemented, and monitored based on the reference model (Principle 3), and agreed project targets, goals, and objectives (Principle 5). See Gann et al. 2019, section 4, part 2, for approaches to ecological restoration.

Remediation following mining uses geomorphic landform design principles to create landforms that are safe, stable and non-polluting (LPSDP 2016*a*, 2016*b*; Rey et al. 2019) to, as much as possible, mimic the topography, hydrology and soils of the target ecosystem (see Jasper & Tashe 2022 in Appendix S2g for further discussion on achieving safe, stable, and nonpolluting landforms for ecological restoration; Cui & Liu 2022 in Appendix S2h for further discussion on water management for the ecological restoration of mine sites). Due to the geological alterations occurring as a result of mining and the reintroduction of component biota into reconstructed landscapes this process is referred to as *reconstruction* (Bradshaw 1983; Cross & Lambers 2017). The biota can then interact with abiotic components to drive further recovery of ecosystem attributes. In some cases where sequential recovery is a characteristic of the ecosystem or is needed (e.g., to help recovery of soils), early successional native species (or even nonnative species where they play a specific soil recovery role such as heavy metal remediation or soil stabilization) may need to be used as early stage colonizing species (Temperton et al. 2004; Cross & Lambers 2017; Kumaresan et al. 2017). In ecosystems that do not exhibit these successional patterns, such as evolutionarily old, biodiverse ecosystems in southwest

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[30] In contrast, there are many native ecosystems that do not exhibit successional phases and will require different approaches to restoration compared to successional ecosystems, for example, the highly biodiverse Cape Floral Kingdom of southern Africa and the Southwest Australian biodiversity hotspots.

[31] Where species volunteer to a post-mined area undergoing restoration (natural regeneration), caution and sound evidence is required to ensure the trajectory and a full species compliment is attained without overdominance of some species.

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Australia (Hopper 2009), most species should be introduced in the initial phases of the restoration program unless they have a potential to establish spontaneously (Rokich 2016; Le Stradic et al. 2018).

### Principle 5 — Assess against Clear Goals and Objectives, Using Measurable Indicators.

In LoM planning, the project scope, vision, targets, goals, and objectives[32] for restoration are identified, along with specific indicators of ecosystem attributes to measure progress. Both ecological and social goals of the project should be included. The importance of the relationship between human well-being and healthy ecosystems (i.e. social-ecological systems, corporate social responsibility, SIA) in environmental planning and management is now well recognized (i.e. ecosystem services) (see Principle 1) (Petkova et al. 2009; Frederiksen 2018; Rosa et al. 2020). After informed, open and meaningful consultation with stakeholders, social goals should be identified in the MCP, including descriptions of the rationale for any trade-offs between ecological and social costs and benefits.

Targets, goals, and objectives[33] in the development of the PMLU are used to evaluate progress throughout closure and relinquishment. It is important to note that the reference model (Principle 3), which draws on many kinds of knowledge (Principle 2), informs the definition of the targets for the PMLU by providing an objective assessment of indicator states relevant to full recovery. However, the full recovery of an ecosystem is not always possible due to irreversible changes resulting from the mining activity, thus the goal comprises measurable standards based on agreed values of the attributes whether it be full or partial recovery (Box 7).

### Box 7 Beyond regulation—setting targets, goals and objectives within a biodiverse semi-arid region.

The Namakwa Sands heavy mineral sand mine is located 385 km north of Cape Town, South Africa, within one of the world's most biodiverse semi-arid region, the Succulent Karoo biome (with 150 mm precipitation per annum). The mine area is large (approximately 13,200 ha, with applications being developed to expand the footprint) but aims to undertake ecological restoration post-mining. The mining company commenced research by generating species-specific understanding for native seeds and nursery-grown production methods. In addition, the company has since developed innovative management systems for (1) topsoil replacement, at a cost to the mine as the resource (heavy minerals) can then not be extracted from these soils, (2) a comprehensive system to stabilize topsoil and combat wind erosion on post-mining land surfaces, and (3) adult transplants, as a large proportion of the plants in this biome are succulents. There is high survivorship in transplanting shrubs directly onto the post-mining landscapes which then provide a seed source for natural regeneration. The mine is now defining goals for native vegetation restoration, and to use success at reaching biodiversity targets to drive further restoration research for improving species recovery. Understanding and setting biodiversity targets for restoration are developed by the mining operator as no such targets are set or assessed by government regulators.

**Project Target**: Namaqualand Duneveld, Namaqualand Strandveld, and Namaqualand Sand Fynbos vegetation types, and mosaics of different vegetation subtypes.

**Project Goals**: The goal is to restore fully functioning resilient and biodiverse ecosystems to a reference condition, that incorporate landscape diversity (not just plot-scale diversity), which is capable of supporting an economically viable land-use (native rangeland grazing).

**Project Objectives**:

- Restore a proportion (e.g., 70% by 2040) of the abundance of native perennial plants found in reference sites.
- Each restoration site to restore a proportion (e.g., 70% by 2040) of the diversity of native perennial plants found in reference sites (alpha diversity).
- Across all restoration sites a proportion (e.g., 70% by 2040) of the diversity across all vegetation types and subtypes (calculated across reference sites) is restored (beta and gamma diversity).
- Each native perennial plant has a grazing value that is equivalent to a proportion (e.g., 70% by 2040) of the value of reference sites.

**Monitoring**: The benchmark quantitative botanical surveys and grazing value assessment are performed by specialists for baseline and mine closure and reassessed every 10 years. In addition, a simplified ongoing monitoring process is performed every 2–5 years to indicate when a recovery toward the reference target is impeded or deviating, by evaluating and integrating the following ecosystem components into one score: native perennial plant abundance, species richness, functional group diversity, and species recruitment conditions. Assessment of recovery is provided (Fig. 10). The full case study for Namakwa Sands mineral sand mine is included as Appendix S1d.

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[32] Terms used here, with some adaptations, are based on those of the Conservation Measures Partnership. (2020) Open Standards for the Practice of Conservation, Version 4.0 and the International Standards. Depending on jurisdiction alternate terminology may be used, but requirements typically follow a similar hierarchical structure detailing broad-level scope through to fine detailed measurable objectives.

[33] See Gann et al. (2019) and Box 5 for a hierarchy of terminology in project planning for restoration.

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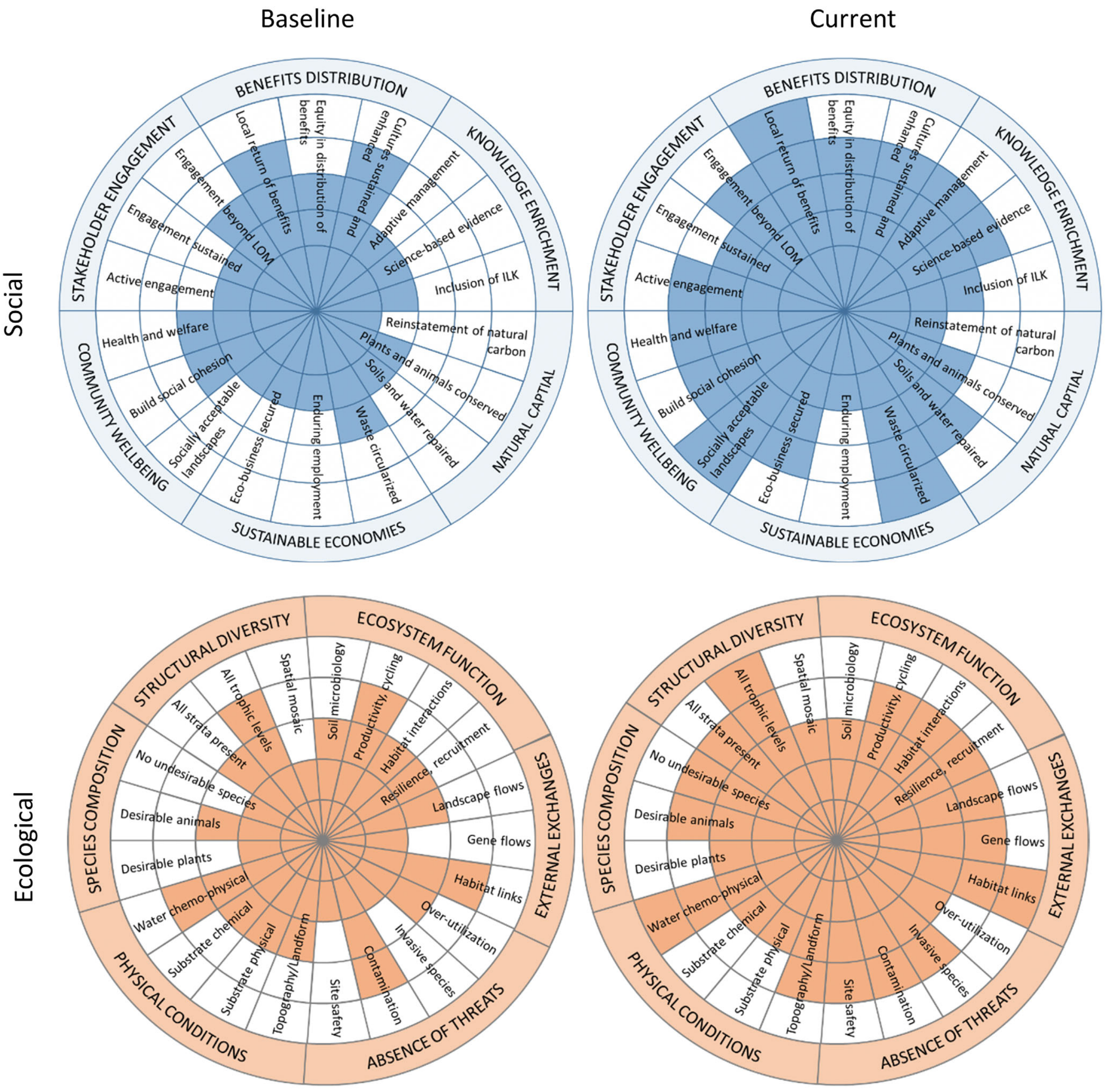

Figure 10. Namakwa Sands mineral sands mine, South Africa, Social Benefits and Ecological Recovery Wheels assessed at post-mining baseline and current conditions.

Due to the substantial changes in the geological profile from mining and a background of continuous environmental change, the expected trajectory of recovery may not be a return to pre-mining conditions. Rather, the recovery trajectory may need to move toward another pre-agreed goal as informed by a reference model (Fig. 11). When progressive restoration is employed, different areas or domains will be at different stages of recovery at any one time. Adequate resources must be allocated over the long-term to allow for effective monitoring, the review of data, progressive evaluation, and adaptive management to inform intervention responses if required.

Setting goals to establish a trajectory in a specific region or site may initially be challenging, with rates of recovery, blocks in the process, and restoration measures yet to be established or understood. Datasets from adjacent sites may be useful, even if older, to inform initial modeling with acknowledgment that additional datasets need to be compiled and models progressively refreshed and revised as new knowledge and technology comes to hand. Confidence in appropriate goal setting will increase as monitoring matures and experience is gained in understanding ecological dynamics of the site during the recovery phase. Nelson (2022) in Appendix S2j provides

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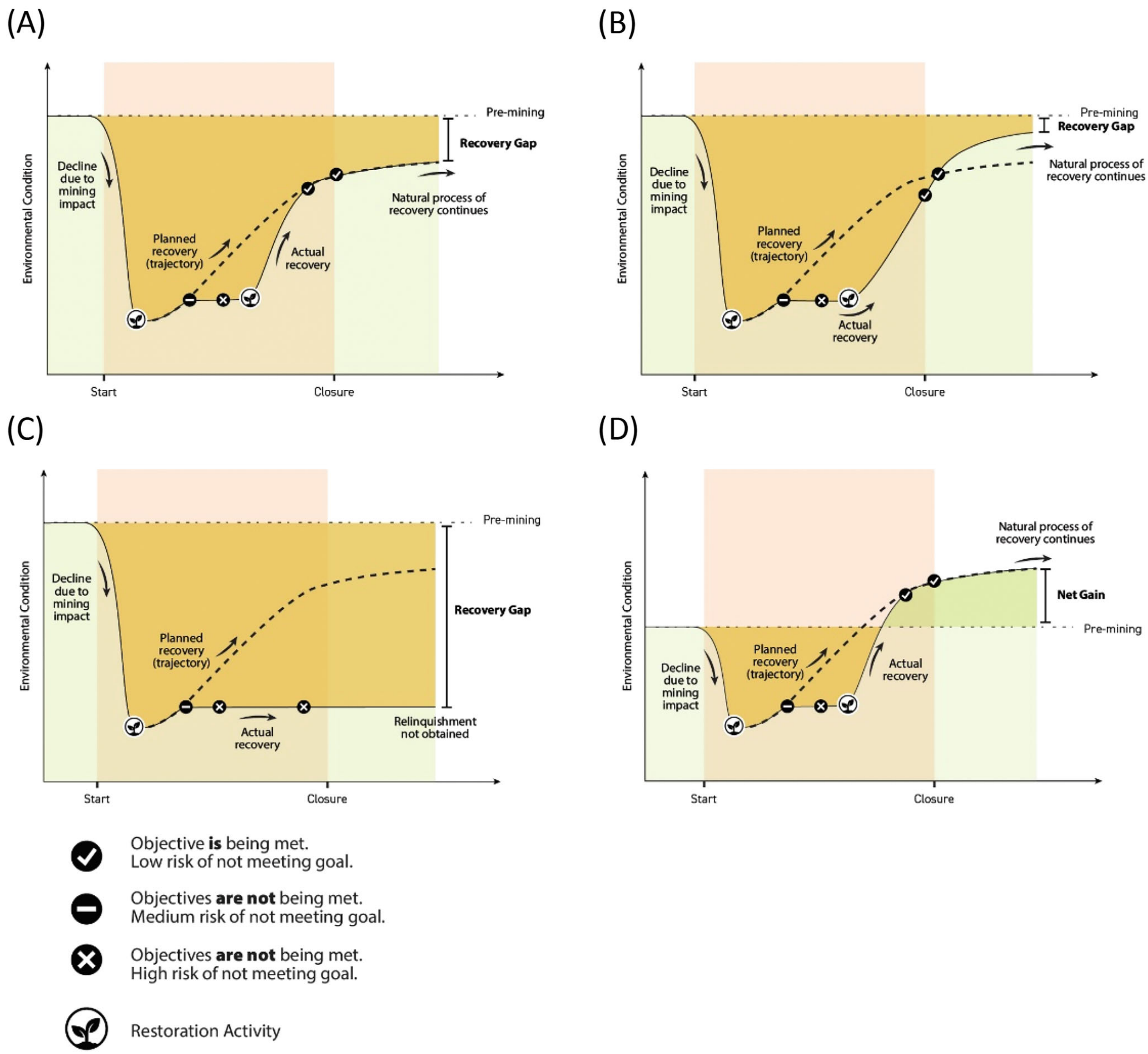

Figure 11. Hypothetical *models of trajectory approaches* for the monitoring of objectives at a restoration site (adapted from Grant 2006; Young et al. 2019). The trajectory of a site may not be linear, nor be expected to return to pre-mining conditions but establishing an estimated trajectory early on allows early detection of remedial actions (if required). The four panels depict ecological restoration post-mining in different pre-mining land uses and adaptive management: (A) mining of a native high-quality ecosystem and undertaking ecological restoration with adaptive management, (B) mining of a native high-quality ecosystem and undertaking ecological restoration with adaptive management and performance exceeds the expected trajectory, (C) mining of a native high-quality ecosystem and undertaking ecological restoration without adaptive management experiencing poor performance resulting in relinquishment not being obtained, and (D) mining in an agricultural or other transformed system where ecological restoration is undertaken once mining ceases and through monitoring and adaptive management net gain is achieved. The recovery gap is the physical or knowledge impediment that cannot be overcome and reflects the discrepancies in biological and functional capacity between the pre-mining state (the baseline and the agreed target reference or, the agreed alternate reference) and what is technologically possible given the best endeavors and science to achieve the reference. The recovery gap represents potential regulatory and social license risks that must be openly conveyed to all stakeholders well ahead of closure.

further detail on monitoring and evaluating the efficacy and effects of mine site restoration. A trajectory may not be linear, with alternatives being curved or stepwise depending on the attribute being measured (Young et al. 2019). Broader influences such as climatic considerations and extreme events (e.g., fire, drought, flood, pest and disease outbreaks) may reset or alter the trajectory of ecological restoration and need to be understood as part of stochastic processes that are inevitable including future climate scenarios (IPCC 2021).

Assessments of progress toward ecological goals should include indicators for each of the six key ecosystem attributes of the reference ecosystem (Principle 3). The same indicators

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**Table 4.** Summary of generic standards for one- to five-star recovery levels. Each level is cumulative. Although this table provides a sketch of what a one- or three-star condition might look like, sites are likely to have different star levels for different attributes at any one time; hence it is preferable to use the Ecological Recovery Wheel, which tracks progress for six key ecosystem attributes through measurements of key indicators (Table 5) (adapted from Gann et al. 2019; Standards Reference Group SERA 2021).

| *Number of stars* | *Summary of recovery outcome* |
|---|---|
| ★ | Over-utilization ceased and land tenure status secured but other threats persisting at high level. Substrates physically and chemically showing some similarity to the reference model and low level of requisite biota present. Foundational level of ecosystem processes, functions, and exchanges present. |
| ★★ | Some remaining threats still high in degree. Physical conditions capable of supporting some biota. Site has a small subset of characteristic requisite species from the reference model with intermediate levels of undesirable species present. Positive exchanges with surrounding environment initiated. |
| ★★★ | Low numbers of threats but still intermediate in degree. An intermediate subset of characteristic requisite species of the reference model is established and are likely to be self-sustaining due to presence of intermediate levels of functions and processes. Positive exchanges with surrounding environment in place for many species and processes. |
| ★★★★ | Threats low in number and degree and physical conditions of high similarity to reference. Based on the reference model, a substantial subset of characteristic biota present (representing all species groupings), along with characteristic structure, and evidence of key functions and processes capable of supporting self-sustaining populations. There are positive exchanges with native ecosystems in the surrounding environment. |
| ★★★★★ | Threats effectively absent. A characteristic assemblage of biota present, exhibiting structural and trophic complexity of very high similarity to the reference model. Self-organizing potential on a trajectory likely to emulate the reference ecosystem functions and processes and are likely to be sustained. Appropriate cross-boundary flows are enabled, and resilience is restored with return of appropriate disturbance regimes. |

are monitored throughout the restoration process to evaluate whether restoration actions are meeting the project's ecological goals and objectives. Each objective must clearly articulate: (1) the indicators that will be measured (e.g., percentage canopy cover of desired plants), (2) desired outcome (e.g., increase, decrease, maintain), (3) desired magnitude of effect (e.g., 40% increase), and (4) time frame (e.g., 5 years). The adoption of findable, accessible, interoperable, reusable (FAIR) knowledge sharing principles underpin rigorous management and stewardship of monitoring data that will extend benefits to the broader restoration community.[34]

For projects where full recovery is undertaken, the ecological target will align with the reference model. When partial recovery is the agreed outcome, the target and reference model may not fully align. For example, the target may lack some species or include surrogates (such as nonnative species where a native reference ecosystem is the target) or allow for low levels of invasive species that cannot be feasibly eradicated, or the ecological targets may be modified to meet social expectations. Ecological restoration in mining landscapes need to be understood within the appropriate time frames, for example, restoration of old-growth ecological functions. Restoration is therefore a long-term activity, with time frames spanning decades, to centuries and beyond (Cross et al. 2017; Nerlekar & Veldman 2020). Ecological recovery may continue long after mine closure and relinquishment. Relinquishment of mine sites may be achieved if ecological recovery can be empirically demonstrated to be on a trajectory toward the target state. This can be challenging to prove and has substantial risks for regulators, stakeholders, or next land users. Schemes such as post-closure trust funds or bonding can provide some surety in the process (Earth Resources Regulation 2018; Tiemann et al. 2019) but should be funded to a level that is reflective of the true cost of restoration.

To achieve successful mine closure and relinquishment, some restoration goals will be more critical than others. These can be identified through a risk-based prioritization process (Young et al. 2019) that helps mining companies allocate resources for appropriate monitoring. This ensures that monitoring will focus on those goals where failure would cause the greatest risk to ecosystem recovery, mine closure, or maintaining SLO, noting that all required goals will need to be met to achieve relinquishment. Monitoring should be linked directly to the restoration goals, allowing any site to be compared with itself, and the agreed reference, over time. As ecological restoration continues, observable progress (or the lack thereof) should be documented and compared against the targets to assess whether the goals have been met or are trending toward the agreed outcomes.

### Principle 6 — Seek the Highest Level of Recovery Attainable.

When implementing restoration of mine sites, the goal should be to achieve the highest level of recovery possible at that site, relative to the six attributes of the reference ecosystem. Recovery, whether full or partial, takes time and, may not be a linear progression (Moreno-Mateos et al. 2020; Nerlekar & Veldman 2020). Mining companies should adopt a policy of building restoration capacity at the commencement of mining, including progressive restoration, continuous improvement, and adaptive management. Such a

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[34] The interoperable Restoration Project Information Sharing Framework (ISF) (Gann et al. 2022), together with SER's Restoration Resource Center, facilitates tracking global progress and trends in ecological restoration, including at mine sites.

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**Table 5.** Sample one- to five-star recovery scale for the six key ecosystem attributes used to measure progress along a trajectory of recovery. This five-star scale represents a gradient from very low to very high similarity to the reference model and is applicable to any level of recovery where a reference model is used. As it is a generic framework for restoration of mined sites, users must develop indicators and monitoring metrics specific to the ecosystem and their key attributes. The starting point of an attribute can be zero or any star level and examples in the table accumulate along the spectrum (adapted from Gann et al. 2019; Standards Reference Group SERA 2021).

| *Attribute* | ★ | ★★ | ★★★ | ★★★★ | ★★★★★ |
|---|---|---|---|---|---|
| Absence of threats | Some direct degradation drivers (e.g., erosion, substrate instability, active contamination) absent and land tenure status secured, but others remain high in number and degree. | Direct degradation drivers (including sources of invasive species, absence of appropriate natural disturbances) intermediate in number and degree. | Number of direct degradation drivers low but some may remain intermediate in degree. | Direct degradation drivers, both external and on-site, low in number and degree. | Threats from direct degradation drivers minimal or effectively absent. |
| Physical conditions | Landforms, and most physical and chemical properties of the site's substrates and hydrology (e.g., soil structure, nutrients, pH, salinity, hydrological conditions) still highly dissimilar to reference ecosystem but some showing improved similarity. | Landforms, and physical and chemical properties of substrates and hydrology, remain at low similarity levels relative to reference model but capable of supporting some biota of reference model. | Landforms similar to the reference model, and physical and chemical properties of substrates and hydrology stabilized within intermediate range of reference model and capable of supporting growth and development of many characteristic biota. | Landforms very similar to the reference model, and physical and chemical conditions of substrates and hydrology highly similar to reference model and suitable for sustained growth and *recruitment* of most characteristic biota. | Landforms very similar to the reference model, and physical and chemical conditions of substrates and hydrology very highly similar to that of the reference model with evidence they can indefinitely sustain all characteristic species and processes. |
| Species composition | Some colonizing species present (e.g., ~2% of the reference model). Very high abundance of nonnative invasive or undesirable species. | A small subset of characteristic species present (e.g., ~10% of the reference model) across site. High to moderate abundance of nonnative invasive or undesirable species. | A subset of key species present (e.g., ~25% of the reference model) over substantial proportions of the site. Moderate to low abundance of nonnative invasive or undesirable species. | Substantial diversity of characteristic species present (e.g., ~60% of the reference model) representing a wide diversity of functional groups. Similar abundance of characteristic species to the reference model. Low to very low abundance of invasive or undesirable species. | High diversity of characteristic species present (e.g., >80% of the reference model) representing a wide diversity of functional groups and high potential for colonization of more native species over time. Highly similar abundance of characteristic species to the reference model. Very low to nil abundance of invasive or undesirable species. |
| Structural diversity | One horizontal stratum of the reference present but *spatial patterning* (including proportion of bare substrate) and community trophic complexity still largely dissimilar to reference model. | Several strata of the reference present and some similarity of spatial patterning and trophic complexity, relative to reference model. | Most strata of the reference present and intermediate similarity of spatial patterning and trophic complexity relative to reference model. | All strata of the reference present and substantial similarity of spatial patterning and trophic complexity relative to reference model. | All strata present and spatial patterning and trophic complexity high. Further complexity and spatial patterning able to self-organize to highly resemble the reference model. |
| Ecosystem function | Processes and functions (e.g., water and nutrient cycling, habitat provision, appropriate disturbance regimes and | Low numbers and levels of physical and biological processes and functions, relative to the reference model | Intermediate numbers and levels of physical and biological processes and functions, relative the | Substantial levels of physical and biological processes and functions, relative to the reference model (including | All functions and processes (including appropriate disturbance regimes) are on a secure trajectory toward the |

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**Table 5.** Continued

| *Attribute* | ★ | ★★ | ★★★ | ★★★★ | ★★★★★ |
|---|---|---|---|---|---|
|  | resilience) are at a very foundational stage only, compared to the reference model. | (incl. plant growth, decomposition, soil processes), are present | reference model (incl. reproduction and dispersal) are present. | return of appropriate disturbance regimes) are present. | levels of the reference and are showing evidence of being sustained. |
| External exchanges | Positive exchanges and flows with surrounding environment (e.g., species, genes, water, fire) in place for only very low numbers of species and processes. | Positive exchanges with surrounding environment in place for a few characteristic species and processes. | Positive exchanges between site and surrounding environment in place for intermediate levels of characteristic species and processes. | Positive exchanges with surrounding environment in place for most characteristic species and processes and likely to be sustained. | Evidence that exchanges with the surrounding environment are highly similar to the reference for all species and processes and likely to be sustained. |

policy can allow managers to continually upgrade and build on project goals to advance recovery toward progressively higher and more enduring outcomes at each new restoration site. It also enables legacy restoration sites to benefit from new knowledge and capacity if they are performing poorly and unable to be relinquished, or if mining companies want to improve outcomes for SLO or other reasons.

One approach for designing projects and tracking progress over time is the use of the Five-star System (Tables 4 & 5) and the Ecological Recovery Wheel (Fig. 12).[35] Both are powerful management tools to assist managers, practitioners, and regulatory authorities to establish, visualize, and communicate the level of recovery aspired to, while also progressively evaluating and tracking the degree of ecosystem recovery over time relative to the reference. These tools provide a means to report changes from the immediate post-mining baseline condition relative to the agreed target. Mine site environmental managers are encouraged to use the Ecological Five-star System and Ecological Recovery Wheel to design and implement projects that aim for the highest possible outcome as well as to monitor and show progress over time, even if full recovery is not initially possible.

### Principle 7 — Gain Cumulative Value when Applied at Large Scales.

Planned mine closures around the world are expected to exponentially increase over the next decade (Fig. 13), offering a rare opportunity to improve performance across sectors in the mining industry (Brock 2020) and to contribute to cumulative value when undertaking ecological restoration and allied restorative activities. Robust regional approaches to adequately plan mine closures and associated restoration are required to maximize cumulative value. Although some mines are small, others may have large footprints (e.g., strip mining) with leases that cover expansive areas, up to 2000 km$^2$ or more (Merritt & Dixon 2011) and consequences extending far beyond the extraction zone. When large areas of land are under tenement, mining companies in consultation with stakeholders can positively influence land management at the landscape scale including both direct and cumulative benefits (Hattingh et al. 2019). Achieving cumulative value from mine site restoration requires planning not only by the mining companies themselves but also through regional government bodies and appropriate stakeholder engagement (Principle 1) throughout the LoM (Sinclair et al. 2022). Mining companies often have strengths in delivering large-scale restoration programs through their investment in research in restoration ecology and sophisticated planning and engineering capabilities.

Areas impacted by mining can provide landscape-scale connectivity and functionality once ecological restoration

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[35] The Five-star System and the Ecological Recovery Wheel are often used in combination to assess recovery level.

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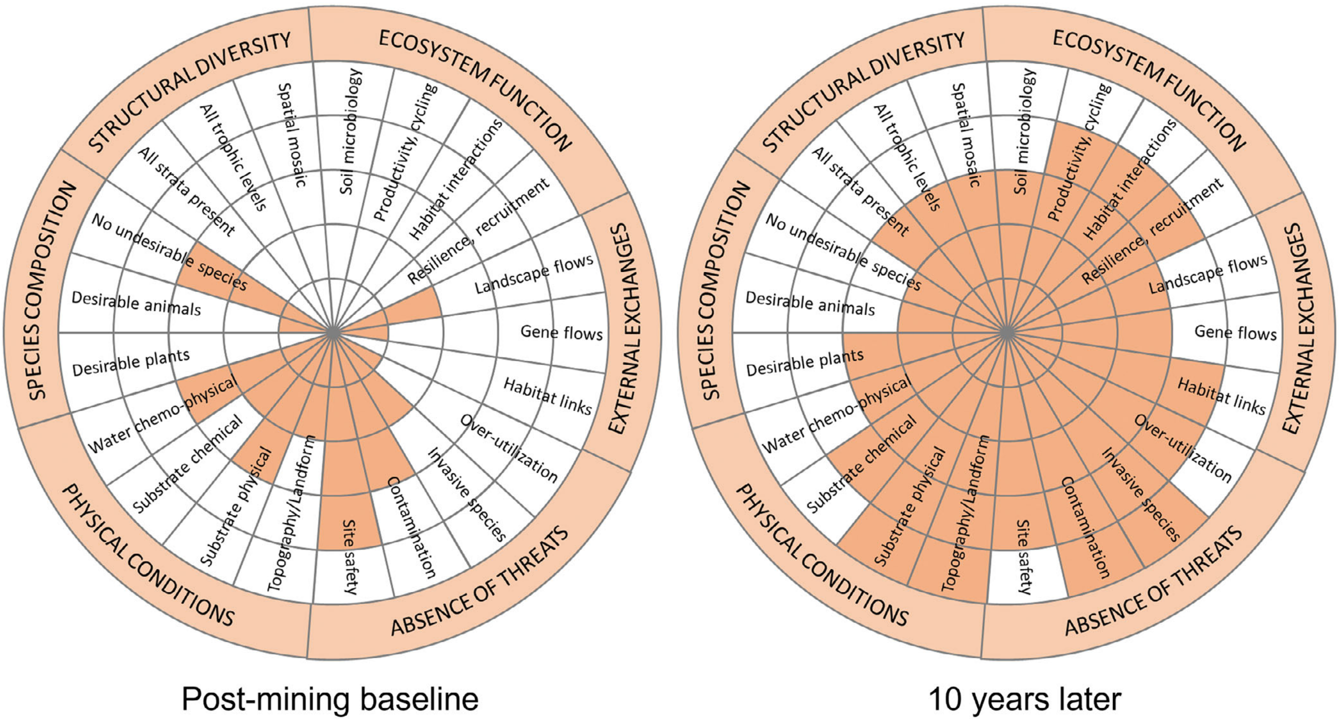

Post-mining baseline

10 years later

Figure 12. The *Mining Ecological Recovery Wheel* conveys progress in the reinstatement of ecosystem attributes relative to the reference model. In this hypothetical example, the left-hand wheel represents the condition of indicators for each of the six attributes before initiation of restoration actions, as determined during the baseline inventory; and the right-hand wheel depicts degree of recovery for each indicator 10 years after initiating restoration actions, based on post-treatment monitoring. In this example, over half of the indicators have attained a four-star condition. To create the recovery wheel, practitioners familiar with the project goals, objectives, site-specific indicators, and recovery levels achieved at specific project dates shade the segments for each indicator after formal or informal evaluation. Blank templates for the wheel are in Appendix S3. Indicator labels can be added or modified to best represent a particular project. (adapted from Gann et al. 2019).

and other restorative activities (Principle 8) are implemented. Because many ecological processes function at landscape, watershed, and regional scales (e.g., *gene flow*, colonization, predation, ecological disturbances), the sequential closure of mines in a region can deliver large-scale restoration if the restoration areas are connected with each other and other native ecosystems, facilitating recovery of ecological processes and movement in response to climate change (McRae et al. 2012). Equally, this landscape-scale approach can emphasize and prioritize the removal of barriers that may impede movement in ecologically important areas, where restoration could be the most effective for improving connectivity (McRae et al. 2012). How a mine integrates with the surrounding environmental and socio-economic landscapes plays a large part in determining its post-closure success (Whitbread-Abrutat et al. 2013). Ecological restoration at the landscape scale includes design with a focus on spatial heterogeneity and ecological integrity.

The implementation of a regional and integrated approach for restoration and other activities as a part of mine closure requires cumulative impact policy and centralized data sharing platforms to support mining companies to achieve scalable impacts beyond their mining tenements. In Australia, the Western Australian Biodiversity Science Institute is leading the development of a platform to allow for dynamic digital assessment of the cumulative environmental, economic, and social impacts which could assist in multiple mine closures and regional planning (WABSI 2019, 2021). The platform is intended to accommodate both impacts from mining and ecological recovery through restoration as well as alternative land uses identified in agreed PMLUs.

### Principle 8 — Employ a Continuum of Restorative Activities.

Ecological restoration at mine sites is one of a "family" of interrelated activities along the Recovery Trajectory for Mine Sites (Fig. 2, adapted from the Restorative Continuum in Gann et al. 2019) that aim to reduce degradation or improve conditions for the partial or full recovery of ecosystems. Besides ecological restoration, other primary categories of activities on the trajectory are minimizing impacts, remediation, and rehabilitation, each of which can be implemented on their own or as a precursor to ecological restoration. Minimizing impacts, remediation, and rehabilitation practices are restorative to the extent that they reduce causes and ongoing impacts of degradation, enhance

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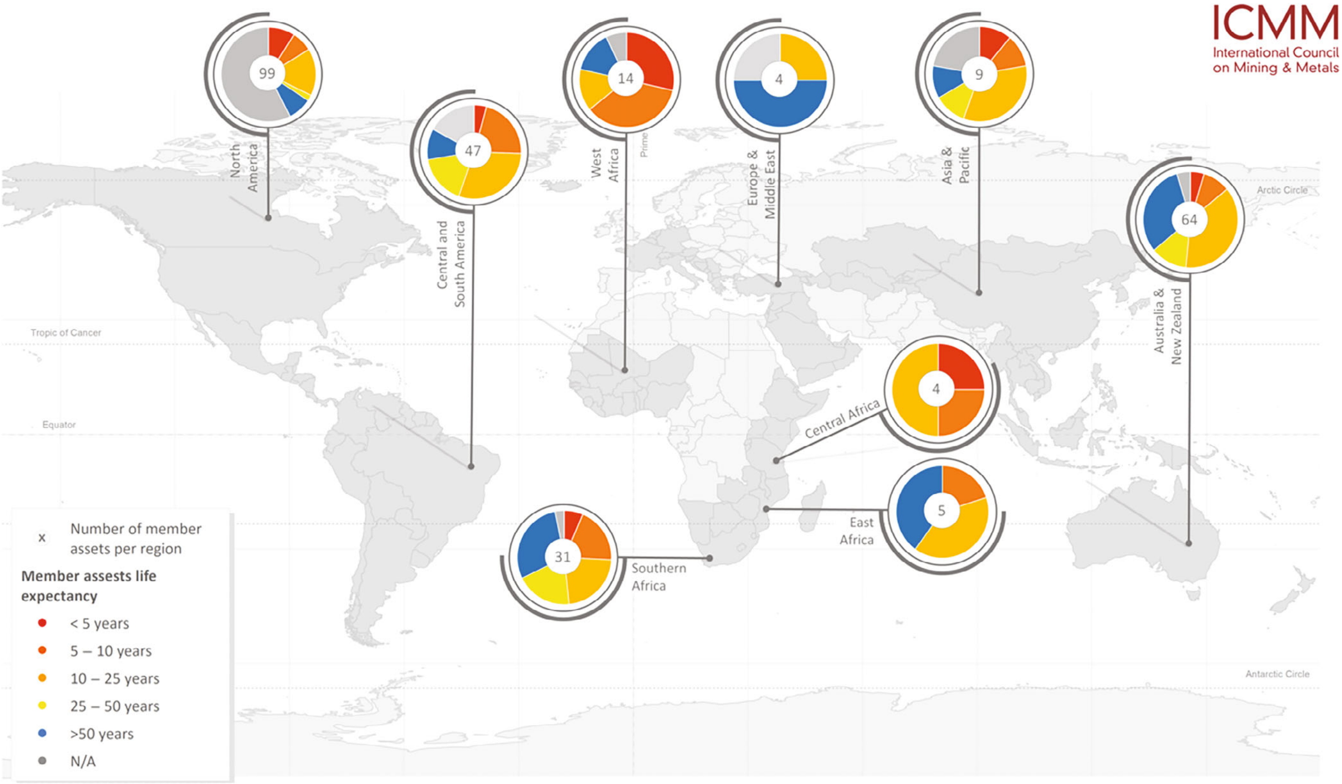

Figure 13. *Projected mine closures around the world* (2018). A survey undertaken by ICMM in 2018 provided information for 441 assets from a total of 18 ICMM member companies, less than half of the total number of members' assets. This is based on 2018 LoM estimates and therefore the findings are indicative, rather than conclusive and will vary depending on commodity prices and future expansion plans (from Brock 2020).

the potential for ecosystem recovery, and promote a transition to a sustainable ecosystem. As such they are also considered allied to ecological restoration. In the context of the UN Decade on Ecosystem Restoration, the full suite of activities on the recovery trajectory can be defined as ecosystem restoration, if they result in net gain to biodiversity, ecosystem health and *integrity*, and human well-being (FAO, International Union for Conservation of Nature [IUCN], CEM, & SER 2021). Activities that do not or will not improve ecological conditions (e.g., revegetation with invasive nonnative species) do not qualify as restorative and do not lead to ecological recovery. The Recovery Trajectory for Mine Sites (Fig. 2) highlights the importance of all restorative activities while pursuing the highest degree of restoration practicable under current social-economic and technical circumstances (Aronson et al. 2017; Liu et al. 2021).[36]

Conceptually, the Recovery Trajectory for Mine Sites offers a holistic approach enabling practitioners to apply the most appropriate and effective treatments given the physical, ecological, social, and financial environments[37] of the mine (both opportunities and constraints). It provides a context for understanding how different activities are interrelated, while also identifying practices best suited to a particular context. Throughout the LoM, different types of restorative activities may form synergistic relationships on the same site. Mechanisms to identify these synergies should be built into mine site management and monitoring plans to act as "check-points" to review, revise, and respond to. Although not restorative per se but consistent with the Mitigation Hierarchy, reducing mining impacts (e.g., reducing energy and water consumption, limiting waste production, minimizing land disturbances, and preventing pollution and the failure of tailings dams) should always be embedded in mine planning and design phases and extend throughout construction and operations. Remediation, including achieving a safe, stable, and nonpolluting landscape, occurs during operations and decommissioning, and should then transition into rehabilitation or ecological restoration (whether partial or full recovery) to the highest level of recovery possible (Principle 6). At closure, a mine site may include a variety of PMLUs. Some may involve repurposing (Box 8), while others may be designated for rehabilitation (Box 9), or ecological restoration.

Ecological restoration and allied activities in the mining context can act as an integrated whole within a broad sustainability paradigm, rather than as disconnected or competing activities. Restorative activities can be cumulatively beneficial, improving

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[36] The Restorative Continuum may be presented in alternative terms in different countries, e.g. in China, *stepwise ecological restoration* is used (Liu et al. 2021), which includes different stages of restorative activities ranging from environmental remediation, ecological rehabilitation, to natural restoration (i.e., natural regeneration).

[37] As mining operates for profit, companies are duty bound to ensure that restitution of post-mined sites is adequately resourced from the outset of mining activities cognizant of the costs, risks, and knowledge-deficits that exist or are likely to emerge during the LoM.

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### Box 8 Managing sites for closure—ecological restoration and repurposing[38]

As mines reach their extractive end point and begin to close, alternative development is often needed to fill the economic gap that results both locally and regionally. This need, together with obligations or company policy to repair environmental impacts of mining, ideally inform the selection of PMLUs. Many forms of mining, including hard rock mining and strip mining, produce areas that may have a substantially altered geological profile or large waste landforms that present major challenges for ecological restoration. These profoundly impacted sites may represent only a portion of the mine footprint, but they can be locations where creative alternate land use considerations are essential in recognition of the need to address the landform challenges. Less impacted areas may be more appropriate locales for ecological restoration. All PMLUs chosen for a site should maximize potential for net gain or improvement for people and nature in conformance with SER's Restorative Continuum (Gann et al. 2019; Principle 8). Importantly, the original approved intent for mine closure and PMLU, ideally as originally developed via the social license to develop a mine, must remain in place until such time as stakeholders agree to altered outcomes.

Alternative post-mining uses are becoming more prominent in severely degraded sites and include examples of mine sites repurposed for tourism such as a former slate mine in Wales, which can be traversed via zipline. Mining infrastructure has been reconfigured as cultural heritage at the Morro Velho mine in Brazil, and conservation and ecosystem services have been combined with recreation at Elliot Lake in Canada. However, such "repurposing" cases are uncommon, particularly since mining is often at very large scales, is remote to communities, and legislation often has a requirement for rehabilitation (Holcombe & Keenan 2020). Such repurposing is clearly dependent on regulatory requirements, the nature of the site, potential demand, and health and safety issues. Research into repurposed PMLUs and how to manage these sustainably along with ecological restoration at sites is a field in its infancy. Holcombe and Keenan (2020) found that the majority of existing repurposing was not led by industry, but rather government and community interests. They also found that mine sites were very often re-used for more than one purpose, indicating that though the previous mining land-use may have been singular, post-mining uses are not (Holcombe & Keenan 2020).

See Beer et al. (2022) in Appendix S2f for a more complete discussion on PMLU and implications.

### Box 9 The ecological value of rehabilitation in an alternative PMLU.

Pan'an Lake National Wetland Park is located in Xuzhou City, China. Following mining for coal, areas were dedicated to alternative ecosystems and land uses such as a collection of ecological wetlands, cultural landscapes, recreation and entertainment areas, and science education facilities. Under the MSRS, the site would be classified as rehabilitation. Management actions have reinstated ecosystem productivity and functioning, with the goal of providing ecosystem services rather than the recovery of a specified target native ecosystem. With modifications some of the restorative activities at the site could transition across the *threshold* from rehabilitation to ecological restoration. A baseline assessment of recovery at the site was completed using the Social Benefits and Ecological Recovery Wheels as a means to focus restoration efforts (Fig. 14). The wheels could also be used to set ecological restoration targets. The full case study of Pan'an Lake National Wetland Park, Xuzhou City, China is available in Appendix S1e.

outcomes from one level to the next. The conceptual frameworks and best practices of ecological restoration conveyed in these MSRS can inspire and inform many actions to improve the overall health and resilience of the environment. Conceptualizing management actions and communicating through the use of the Recovery Trajectory for Mine Sites can assist mining companies, governments, associated industries, and communities to develop a trusted relationship and maximize improvements in ecological conditions that will accelerate positive change at larger scales (see Principle 7). Where ecological restoration is inappropriate or not viable (e.g., rehabilitation the only option), restorative work should aim for the highest possible recovery. As with ecological restoration, small and ongoing improvements can be cumulative at larger scales for allied activities. Finally, if a portion of a mine site is repurposed, the use should be sustainable and compatible with restorative activities also planned for the site and meet community and cultural expectations.

## Section 4 — Standards of Practice for Planning and Implementing Mine Site Restoration Projects

The following lists specific standard practices recommended for use in mine site restoration and recovery, including rehabilitation and reclamation. They include practices used in: (1) planning and design, (2) implementation, (3) monitoring and evaluation, and (4) ongoing activities and maintenance. These SoP are consistent with SER's Code of Ethics (SER 2021) and other relevant guidance, and are adapted from the International Standards (Gann

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[38] Box 8 was written by Prof. Andrew Beer (University of South Australia), Sarah Holcombe (University of Queensland), Renee Young (The Western Australian Biodiversity Science Institute), and Sally Weller (University of South Australia). A full discussion on the topic is provided in Appendix S2f.

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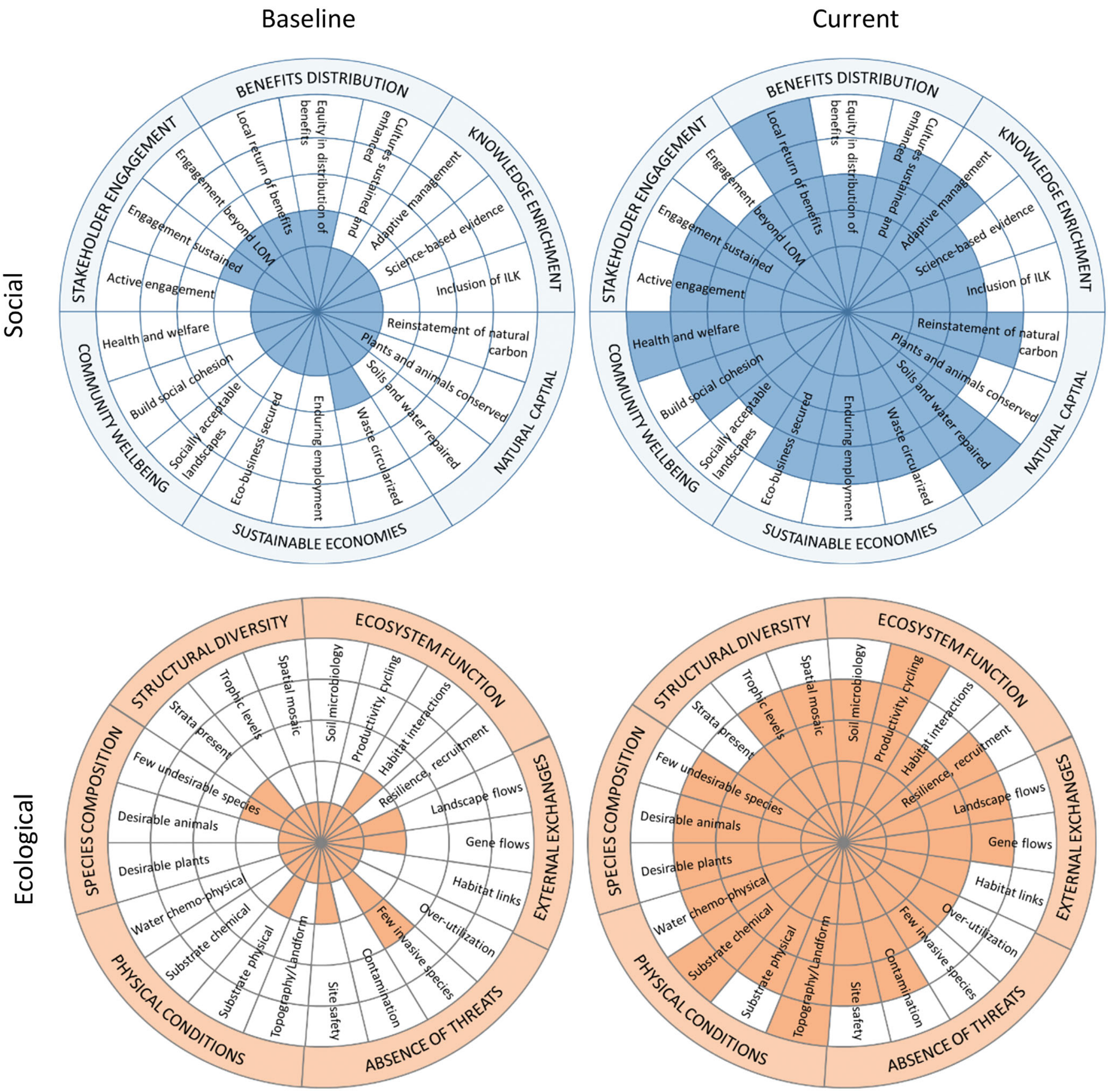

Figure 14. Pan'an Lake National Wetland Park, Xuzhou City, China, Social Benefits and Ecological Recovery Wheels assessed at post-mining baseline and against *rehabilitation* targets (note sub-attributes in the Ecological Recovery Wheel have been modified in this case study). Additional restorative actions could shift recovery from rehabilitation to ecological restoration, which would require the development of a new Ecological Recovery Wheel to indicate new targets based on a native reference ecosystem.

et al. 2019).[39] They are adjustable to the size, complexity, commodity, geographical location, climate, degree of degradation, and regulatory status of mine site restoration projects, but not all steps will apply to all projects. They can be used to inform EMPs and other planning and regulatory documents. The steps described in the standards are not always sequential. For instance, the standards related to monitoring are placed after implementation because the bulk of the monitoring effort may occur post-treatment; however, activities critical to monitoring must begin prior to and during the project development phase because of the need to design monitoring plans, develop budgets, secure funding, and collect pre-impact data prior to the implementation of restoration treatments.

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[39] Relevant guidance includes the Guiding Principles for Ecosystem Restoration (United Nations 2021), and the ICMM Mining Principles and Performance Expectations (ICMM 2020).

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1. Planning and design

    1.1 **Stakeholder engagement**. Meaningful, informed, and transparent engagement is undertaken at the initial planning stage of a restoration project with key stakeholders (including Indigenous communities,[40] land or water rights owners, site managers, industry interest groups, neighbors, and local communities) and continues throughout LoM and the duration of the mine site restoration project particularly when practices or new knowledge may lead to a revised restoration outcome. Key steps are to:

        1.1.1 Include a schedule for stakeholder engagement throughout LoM. Where possible, participatory planning and restoration plan co-design are implemented, and local community capacity building and training are included (see tool: Stakeholder Research Toolkit; ICMM 2015).

        1.1.2 Perform due diligence to ensure that stakeholder rights, including land ownership and tenure, and Indigenous rights and interests as required by FPIC principles, are understood, respected, and appropriately addressed throughout the mine site restoration process with reengagement if restoration plans or predicted outcomes change.

        1.1.3 Ensure culturally and socially appropriate consultation is undertaken, particularly when involving traditional custodians of land, while avoiding stakeholder fatigue due to over-consultation. Ethical principles such as respect for ILK, intellectual property, and cultural safety will be necessary for interactions with Indigenous stakeholders.

    1.2 **Legal approvals**. Identify all regulatory and statutory approvals to be obtained prior and throughout LoM and incorporate activities and reporting into operational and management planning.

    1.3 **Context assessment.** Plans and stakeholder engagement are informed by local and regional goals, priorities, and spatial planning, and:

        1.3.1 Include diagrams or maps of the project in relation to the surrounding landscape or aquatic environment.

        1.3.2 Assess and plan for amelioration of cumulative impact of mining in the region, including impacts on environmental, social, economic, and cultural values.

        1.3.3 Identify ways to improve beneficial connectivity between habitats at the restoration site, and increase beneficial external ecological exchanges with nearby native ecosystems to improve *landscape-level flows* and processes, including colonization and genetic exchange between sites.

        1.3.4 Identify areas that can be utilized as reference sites and act as donor sites for seeds and other sources of materials ensuring compliance with all SoP for sourcing plants, animals, and other biota (see appendix 1 of Gann et al. 2019; Pedrini & Dixon 2020).

        1.3.5 Specify strategies to ensure continuity of future management to align and integrate the project with management of nearby environments, including native ecosystems and productive landscapes.

    1.4 **Assessment of security of site tenure and scheduling of post-restoration maintenance**. When the PMLU is a native ecosystem, evidence of long-term conservation management is a requisite before relinquishment. Plans:

        1.4.1 Identify site-tenure security to enable long-term restoration and allow appropriate ongoing access for monitoring and management including future interventions.

        1.4.2 Implement measures to protect the site from threats such as harm from direct human impacts, including deleterious management, invasive species, and pathogens.

        1.4.3 Develop and incorporate a plan including ongoing funding for aftercare and site maintenance after restoration works to ensure long-term sustainability and resilience of the restoration site.

    1.5 **Pre- and post-mining baseline inventory**. The pre- and post-mining baseline inventories document the causes, intensity, and extent of degradation, and describes the effects of degradation on the biota and physical environment relative to the six ecosystem attributes. Accordingly, plans:

        1.5.1 Identify and map the geographic distribution of native, ruderal, and nonnative species at the site to be mined, particularly threatened or culturally significant species or communities and invasive species. Restoration plans clearly articulate:

            - Protocols for trialing of restoration approaches so that by closure, the impacted species and ecosystems can be proven to be on a trajectory of recovery toward the agreed target.
            - Restoration strategies for mining-impacted flora and fauna that are of conservation significance (e.g., threatened species) or have cultural value (e.g., food, fiber, medicinal or totemic) requiring ex situ conservation and *reintroduction*; appropriate and effective ex situ conservation strategies as a safety-net for species or populations affected by mining, including the development of propagation and captive breeding programs when required supplemented by ex situ storage of seed/somatic tissue/diaspores, or operation of ex situ breeding facilities or plant collections.
            - Restoration strategies for significant ecosystems, that demonstrate reinstatement of a fully competent, comprehensive, and representative suite of species indicative of the pre-mining impacted ecosystem. Habitat and restoration requirements for the ecosystem to support healthy, resilient, and sustainable populations

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[40] In some countries, the term stakeholder should not be applied to Indigenous people because of their constitutionally protected rights and expectations to interact with governments on a nation to nation basis (Porter 2006).

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that demonstrate a capacity to recover at the restored site including proven trajectories for old-growth capacity to be attained.

1.5.2 Record status of current abiotic conditions (through photographs, metrics, and other means) including dimensions, configuration, and physical and chemical condition of streams, water bodies, water column, land surfaces, soils, or any other material elements, relative to prior or changing conditions.

1.5.3 Detect type and degree of drivers and threats (including and in addition to mining) that have caused or may cause degradation on the site and ways to eliminate, mitigate, or adapt to them (for a standard threats taxonomy, see the Open Standards for the Practice of Conservation [Conservation Standards] Threats Classification[41]). This includes the assessment of:

- Extant ecosystems that are being mined and then restored, pre-existing intact ecosystems must be mapped in detail prior to site disturbance (see also list 1.6 below).
- Historical, current, and anticipated impacts within and external to the site (e.g., over-utilization, sedimentation, fragmentation, pest plants and animals, hydrological impacts, contamination, altered disturbance regimes) and ways to manage, remove, or adapt to them.
- Description of needs for genetic supplementation for species reduced to nonviable populations due to fragmentation (see appendix 1 of Gann et al. 2019).
- Current and anticipated effects of climate change (e.g., temperature, rainfall, sea level, episodic events) on species and genotypes with respect to likely future viability of restored site based on empirical evidence.
- The potential impact of development other than mining, such as forestry, agriculture, and recreational use, to induce changes that affect restoration at the site. These activities may not be present at the start of a mining project but could develop over the LoM, or after relinquishment. Thus, they may not be identified in the cumulative impact assessment.

1.5.4 Identify the relative capacity of the biota on site or external to the site to commence and continue recovery with or without assistance. This includes undertaking an inventory that includes:

- A list of native and nonnative species presumed absent and those potentially persisting as propagules or occurring within colonization distance.
- A map of areas of distinct conditions, including successional stages of ecosystems present, priority recovery areas, and any distinct spatial areas requiring different treatments.
- Strategies to manage invasive species that may compete with native biota.

1.6 **Reference ecosystem(s) and reference models**. Plans identify and map reference ecosystems, sites and include appropriate reference models for distinct areas (domains) of the mine site (Principle 3) based on multiple indicators of the six key ecosystem attributes (Table 3). In some cases, descriptions of intact ecosystems may be available from previous assessments or models, peer-reviewed publications, or environmental agency guidelines. Specifically, plans:

1.6.1 Document substrate and geomorphological characteristics (biotic or abiotic, aquatic, or terrestrial).

1.6.2 List major characteristic and iconic species (representing all plant growth forms and functional groups of microfauna and macrofauna, which may include pioneer and rare or threatened species).

1.6.3 Identify the ecosystem's functional attributes to the extent possible, including nutrient cycles, characteristic disturbance and flow regimes, successional pathways, plant–animal interactions, plant–microbe interactions, ecosystem exchanges, and any disturbance-dependence of component species.

1.6.4 Note any ecological mosaics that require use of multiple reference ecosystems on a site.

1.6.5 Assess habitat needs of focal biota (including any faunal minimum ranges and responses to degradation pressures and restoration treatments).

1.6.6 Incorporate climate modeling to assess the resilience of the target ecosystem to potential future environmental conditions and implement adaptive actions based on best available knowledge.

1.7 **Vision, targets, goals, and objectives**. Clear and measurable (specific, measurable, achievable, results-oriented, and time-limited [SMART]) goals and objectives are used to identify the most appropriate actions, ensure that all project participants and stakeholders have a common understanding of the project, and measures of progress (see Monitoring below). Plans must clearly state:

1.7.1 Project vision and ecological and social targets, including a description of the mine site and the ecosystem to be restored.

1.7.2 Ecological and social goals including level of ecological recovery sought (i.e. conditions or states of the ecosystem attributes to be achieved). In full recovery cases, this will fully align with the reference model, whereas in partial recovery cases this will include elements that deviate from the reference to some degree. Ecological goals quantify, where possible, degree of the reference ecosystem attributes to be attained. The social goals must be explicit, considering the time frame,

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[41] https://conservationstandards.org/library-item/direct-threats-classification-v2-0/

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intergenerational equity, and social capital available in the area. Highest practicable ecological and social outcomes in post-mining landscapes are sought.

1.7.3 Objectives assess progress toward a goal by measuring interim results achieved by set time periods. In addition to ecological and social indicators, objectives should include actions and quantities so that they are clear and specific. Objectives should be developed based on theories of change to test assumptions regarding ecological recovery.

1.8 **Restoration treatment prescriptions**. Plans contain clearly stated treatment prescriptions for each distinct restoration area (domain), or restorative activity, describing what, where, and by whom treatments will be undertaken, and their order or priority, while considering local legal frameworks. Where knowledge or experience is lacking, adaptive management or targeted research that informs appropriate prescriptions is necessary noting that long time frames may be required in research programs. The Precautionary Principle is applied in a manner that reduces environmental risk. Plans:

1.8.1 Describe actions to be undertaken to eliminate and mitigate, or adapt to causal problems.

1.8.2 Identify and justify specific restoration or restorative approaches, descriptions of specific treatments for each area (domain) to be treated, and prioritization of actions. Depending on the condition of the site, this includes identification of:

- Amendments to the shape, configuration, chemistry, or other physical condition of abiotic elements to render the mine site safe, stable, and nonpolluting.
- Amendments to the shape, configuration, chemistry, or other physical condition of abiotic elements to render them amenable to the recovery of focal biota and ecosystem structure and functions.
- Effective and ecologically appropriate strategies, techniques, and technologies that are available or must be developed to control undesirable species, and to protect and optimize recovery of *desirable species* and their habitats on site.
- Ecologically appropriate methods (e.g., topsoil, seeding, plantings) to assist natural regeneration including the reintroduction of missing species, or to *augment* or reinforce populations (i.e., translocations[42]).
- Appropriate species selection, genetic resources, and procurement of biota to be reintroduced (see appendix 1 in Gann et al. 2019) ensuring that procurement of seed or plants is scheduled to allow time for supply (i.e., seed collections are adequate; plant propagation is achievable and that seed diversity and quantities are sufficient for the restoration program).
- Ecologically appropriate strategies to address circumstances where the ideal species or genetic stock is not immediately available (e.g., leaving gaps for in-fill reintroductions in subsequent seasons) including retro-fitting sites that have already undergone restoration activities or treatments.

1.9 **Analyzing logistics**. Analysis of potential for resourcing the mine site restoration project and of likely risks is required before executing a restoration plan. To address practical constraints and opportunities, plans:

1.9.1 Obtain permissions and permits and address legal constraints applying to the site and the project, including land-tenure and ownership claims.

1.9.2 Identify funding, labor (including appropriate skill level), and other resources that will enable appropriate treatments (including follow-up treatments and monitoring), until the site reaches a stabilized condition.

1.9.3 Implement education and training to ensure tasks will be completed by personnel competent in understanding biotic and abiotic issues associated with restoration.

1.9.4 Ensure that scheduling supply of seeds, plants, and other key materials allows adequate time for (e.g., for collection of needed diversity and quantity of seed, plant propagation, and growth).

1.9.5 Identify site infrastructure (e.g., roads, power, offices, workshops) to be removed or retained and maintained at the site and those responsible for ongoing restoration and site management until an agreed upon relinquishment stage is reached.

1.9.6 Undertake a full risk and opportunity assessment and identify a risk-management strategy for the project, particularly including contingency arrangements for unexpected changes in environmental conditions, financing, or human resourcing.

1.9.7 Develop a project timetable and rationale for the duration of the project (e.g., using a schedule planning chart).

1.9.8 Identify ways to maintain commitment to the project's goals, and objectives over the life of the project, including political and financial support.

1.10 **Establishing a process for restoration review**. Plans include a schedule and time frame to:

1.10.1 Undertake regulator, stakeholder, and independent peer review of restoration plans, implementation, monitoring, evaluation, and reporting as required including when

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[42] Translocation includes three different practices: (1) augmentation or reinforcement of species already present at the restoration site; (2) reintroduction of species previously documented at the site or the immediate vicinity of the site; and (3) introduction of appropriate species not previously documented within the site. Translocations may involve plants, animals, or other biota (e.g., fungi).

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restoration plans alter or are subject to new knowledge.
    - 1.10.2 Schedule reviews of planning documents to accommodate new knowledge, improved restoration technology, changing environmental conditions, and lessons learned.
    - 1.10.3 Respond to an altered or unsatisfactory trajectory with the technical competency to rapidly generate the knowledge needed to review and modify plans and undertake appropriate actions.

2. Implementation

The implementation phase may be of short or long duration, depending on the mine site restoration project, strategies, and impacted biota and ecosystems. Monitoring and adaptive management may dictate additional restoration interventions after an initial project or stage has been completed.
During the implementation phase, mine site restoration projects are managed to:

- 2.1 **Protect the site from collateral impacts**. No further or lasting damage is caused by the restoration works to any natural resources or elements of the terrestrial or aquatic area impacted by the project, including physical damage (e.g., clearing, burying topsoil, soil compaction), chemical contamination (e.g., inappropriate fertilizer, pesticide use) or biological contamination (e.g., introduction of weeds, pests, and disease).
- 2.2 **Engage appropriate participants**. Restoration treatments are interpreted and implemented responsibly, effectively, and efficiently by, and under the supervision of, suitably qualified, skilled, and locally experienced practitioners or well-trained employees or contractors of the mining company. Where possible, use of sustainable materials and processes are incorporated into restoration projects.
- 2.3 **Incorporate natural processes supported by environmental engineering**. Treatments are undertaken in a manner that is responsive to natural processes, and that fosters and protects the potential for natural and assisted recovery. Primary treatments including substrate and hydrological amendments, pest animal and plant control, and biotic reintroductions, which are supported by supplementary treatments as required. Because the recovery period may be over long periods, interim treatments to reduce adverse effects (e.g., weed establishment) are planned for, budgeted, and implemented. Appropriate aftercare is provided to any plantings or translocated fauna.
- 2.4 **Respond to changes occurring on site**. Adaptive management is applied, informed by the results of timely, and ecologically appropriate monitoring. This approach includes both corrective changes to adapt to unexpected ecosystem responses and additional work or research as needed. In some cases, additional or new research may be required to overcome particular restoration impediments, which is budgeted for during the planning stages.
- 2.5 **Ensure compliance**. Projects comply with work, health, and safety legislation. All applicable laws and regulations are followed, and permits in place, including those related to soil, air, water, oceans, heritage, species, ecosystem conservation, and labor.
- 2.6 **Communicate with stakeholders beyond regulatory reporting**. Relevant company personnel communicate regularly with key stakeholders (preferably through a communications plan, integrated with any stakeholder engagement and citizen-science activities) to inform them of progress and engage them in the implementation of the restoration project to ensure their feedback is incorporated into mine planning and restoration, particularly if the recovery trajectory is altered or altering. Inform stakeholders about how their views have been incorporated into forward planning processes.

3. Monitoring, documentation, evaluation, and reporting

Restoration projects at mine sites adopt the principle of observing and recording treatments and responses to determine whether a project is on track to meet goals and objectives. Projects are regularly assessed and analyzed against a trajectory to adjust treatments as required (i.e. using an adaptive-management framework). Collaborations are promoted between researchers, government agencies, local-knowledge experts, and practitioners, especially where treatments are emerging innovations or being applied at a large scale. Monitoring needs are reassessed throughout the project and resources reallocated or adapted accordingly.

- 3.1 **Monitoring design**. Monitoring mine site restoration outcomes begins at the planning stage by developing a monitoring plan to identify treatment effectiveness. This plan includes specific areas to be addressed through monitoring; the selection of suitable indicators; sampling design for collecting pre- and post-mining baseline implementation, and post-treatment data; procedures for documenting and archiving collected data; plans for learning from failure; plans for data analysis; plans for communicating results and lessons learned to regulators and stakeholders; and processes for monitoring data to inform adaptive management practices.
    - 3.1.1 Monitoring is geared to specific targets and measurable goals and objectives identified at the start of the project. Once indicators are determined, pre- and post-mining baseline data are collected and milestones established to gauge whether the rate of progress and planned trajectory are satisfactory. In addition, identification of points of substantial recovery or triggers along the path of trajectory can be helpful; if the data reach a trigger point, then corrective actions may be needed.
    - 3.1.2 Monitoring methods are appropriate to the goals and scale of the project. Whenever possible, methods are easy-to-use, and implemented by experienced practitioners or through targeted

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participatory processes. When formal quantitative sampling is needed, the sampling design must include a sufficiently large sample size to enable statistical analyses. In all cases the methods are sufficiently detailed to be repeatable in future years.

3.1.3 Monitoring methodologies are applied dependent on scale, with emerging technologies (e.g., remote sensing, eDNA) adopted where they are appropriate, effective and efficient, and applicable to the site issues in question.

3.1.4 Project managers are mindful that monitoring is essential to determine and demonstrate to regulators and stakeholders whether goals are met and to improve outcomes through adaptive management. Involving regulators and stakeholders in project design and data collection and analysis helps improve collaborative decision-making, creates a sense of ownership and engagement, to maintain longer-term stakeholder interest, and strengthen stakeholder capacity, empowerment, and trust. Monitoring must have built-in opportunities for learning and adaptation.

3.2 **Records management.** Adequate, secure, permanent and accessible records of all mine site restoration project data, including documents related to planning, implementation, monitoring, and reporting are maintained to inform adaptive management and enable future evaluation of responses to treatments. All treatment data, including details of restoration activities, number of work sessions and costs, and monitoring and evaluation records are maintained for future reference. Provenance data includes location (preferably GPS-derived) and description of donor and receiving sites or populations. Documentation includes reference to scientifically accepted collection protocols, date of acquisition, identification procedures, and collector/propagator's name. In addition:

3.2.1 Consideration is given to allowing data to be open access following FAIR principles, or adding results to open access repositories such as SER's Restoration Resource Center or other national or international databases.

3.2.2 Data are archived in secure, accessible storage and accessibility is definfed and transparent. Metadata describing the contents of each dataset are included.

3.2.3 Incoming staff and collaborators are apprised of the nature, scope, and accessibility of environmental records to ensure retained corporate knowledge and experience is maintained and forms an integral part of future restoration planning.

3.3 **Evaluating outcomes.** Evaluation of the outcomes of the restoration works, with progress assessed against project goals, and objectives, is essential. This requires use of an evaluation tool (e.g., the Five-star System presented in Principle 5; the Audit Tool of the Conservation Standards[43] among others, or conventional ecological evaluation methods).

3.3.1 Evaluation adequately assesses results from the monitoring.

3.3.2 Results inform and guide ongoing and adaptive management.

3.3.3 Adaptive management is incorporated into restoration planning to establish or return to a restorative trajectory toward agreed targets with appropriate stakeholder consultation, planning, and budgeting.

3.4 **Reporting to interested parties.** Reporting involves preparing and disseminating progress reports that detail evaluation results for regulators, stakeholders, and broader interest groups (e.g., general media, topical newsletters, and scientific journals) to convey outputs and outcomes as they become available.

3.4.1 Reporting conveys the information accurately and is accessible to all audiences (including non-traditional language groups and Indigenous and local communities) with transparency of the underlying data (i.e., supplementary data) to enable scrutiny.

3.4.2 Reporting specifies the level and details of monitoring upon which any evaluation of progress has been based.

3.4.3 Direct alerts to stakeholders particularly for Indigenous and local communities to ensure variations to a restoration plan are conveyed and feedback is incorporated into the modified approaches.

4. Ongoing activities and maintenance

4.1 **The mining company (pre-relinquishment) and management body of the next PMLU (post-relinquishment) is responsible for ongoing interventions (toward restoration goals) and maintenance** (after restoration goals have been met) to prevent deleterious impacts and undertake post-project completion monitoring to avoid regression into a degraded state. This requirement is considered in budgets prior to restoration. Comparison to an appropriate reference model is ongoing and includes:

1. Regular surveillance of the site, ideally involving industry, landowners, and stakeholders, to check for re-occurrence of degradation to protect the investment in restoration.
2. Adaptive management built into operations of the managing organization, working in collaboration with industry, regulators and stakeholders as required.
3. Where the agreed upon PMLU allows access, develop or support stewardship programs for local communities, including Indigenous groups to improve land management of the site post-relinquishment.

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[43] https://conservationstandards.org/2018/12/14/conservation-audit-tool-ready-for-use/

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4. Ongoing communication about restoration outcomes and trajectory is undertaken to ensure that the restoration project and past investments are valued by, for example:
   - continuing cultural activities that maintain the history of the project and celebrate its achievements.
   - reinforcing lessons learned including the opportunity to undertake similar projects elsewhere.

## Section 5 — Conclusion

The mining sector has a pivotal role to play in addressing the global threats of climate change, land degradation and desertification, and biodiversity loss and the impacts of these crises to human health and well-being. Even a complete shift to renewable energies would require vast amounts of raw materials such as graphite, cobalt, and lithium. This demand will see many new mines open and others will close. Although mine closure and stabilization practices are well-understood and often well-regulated, the same is not yet true for the restoration of mine sites. The International Principles and Standards for the Ecological Restoration and Recovery of Mine Sites provide a framework to fill this gap and to create opportunities for the mining sector to not just create safe, stable and nonpolluting conditions post-mining, but to implement high-impact ecological restoration that will benefit both people and nature. This begins of course with the Mitigation Hierarchy to avoid impacting irreplaceable, unique, or high-value natural and cultural assets. Where mining does occur, practices guided by the eight principles in the MSRS will help minimize the recovery gap and return functional, climate resilient ecosystems. Communities and regulatory agencies are increasingly likely to pressure companies to engage in off site recovery of legacy mines and other adjacent landscapes to create ecological and social net gain by restoring more than what was impacted. Innovations in mine site restoration can also help improve restoration in other highly degraded landscapes, especially through transparent and proactive knowledge sharing. The global mining footprint is profound, requiring an equally profound globally scaled investment in the restoration of mine sites. It is time for the mining industry to harness its technological capacity and financial resources, in combination with the guidance and tools in the MSRS, to implement restoration at scale to actively advance the UN Sustainable Development Goals and improve the health and well-being of both people and nature.

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## Glossary of Terms

This glossary is adapted and expanded from McDonald et al. (2016), Gann et al. (2019), and Standards Reference Group (2021).

**Abiotic:** non-living materials and conditions within a given ecosystem, including rock, mineral earth, or aqueous substrate, the atmosphere, weather and climate, topographic relief and aspect, and nutrient, hydrological, fire, and salinity regimes.

**Adaptive management:** iterative process for improving management policies and practices by applying knowledge learned through the assessment of previously employed policies and practices to future projects and programs. It is the practice of revisiting management decisions and revising them in light of new information. See also Future Practice.

**Aftercare:** special care given to plants and animals during the establishment period, including watering, weeding, pest and disease control, and supplemental fertilization or feeding.

**Allied activities:** restorative practices (including environmental improvement, remediation, and rehabilitation) that reduce the causes and ongoing effects of degradation and enhance potential for ecosystem recovery.

**Attributes:** see Key ecosystem attributes.

**Augment, Augmentation** (of depleted populations): (also known as enhancement, enrichment, reinforcement, replenishment, or restocking) adding seeds or individuals of a population to the same population, with the aim of increasing population size or genetic diversity and thereby improving viability; re-creating a recently extirpated population with individuals propagated from that population. In common practice, populations are often augmented with material from other nearby populations, not just the same population.

**Barriers** (to recovery): factors impeding recovery of an ecosystem attribute.

**Baseline condition:** the condition of the restoration site immediately prior to the initiation of ecological restoration activities.

**Baseline inventory:** an assessment of current biotic and abiotic elements of a site prior to ecological restoration, including its compositional, structural, and functional attributes. The inventory is implemented at the commencement of the restoration planning stage, along with the development of a reference model, to inform planning including restoration goals, measurable objectives, and treatment prescriptions. See also pre- and post-mining baseline.

**Biodiversity:** the variability of living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within genes, species, between species, and of ecosystems.

**Carbon sequestration:** the capture and long-term storage of atmospheric carbon dioxide (typically in biomass accumulation by way of photosynthesis, vegetation growth, and soil organic matter build-up). This may occur naturally or be the result of actions such as engineered drawdown to reduce the impacts of climate change.

**Climate readiness:** refers to a circumstance where organisms used in restoration have been selected, based on climate science and genetics, to improve the likelihood of a species persisting under anticipated or potential climate change.

**Cycling** (ecological): the transfer (between parts of an ecosystem) of resources such as water, carbon, nitrogen, and other elements that are fundamental to other ecosystem functions.

**Damage** (to ecosystem): an acute and obvious deleterious impact on an ecosystem.

**Degradation** (of an ecosystem): a level of deleterious human impact to ecosystems that results in the loss of biodiversity and simplification or disruption in their composition, structure, and functioning, and generally leads to a reduction in the provision of ecosystem services.

**Desirable species:** species from the reference ecosystem (or sometimes nonnative nurse or stabilizing species) that will enable the native ecosystem to recover. The corollary of desirable species is undesirable species, which are often nonnative species but can include native species that become overabundant due to degradation or restoration processes.

**Destruction** (of an ecosystem): when degradation or damage removes all macroscopic life, and commonly destroys or disrupts the physical environment of an ecosystem.

**Disturbance regime:** the pattern, frequency, timing, or occurrence of disturbance events that are characteristic of an ecosystem over a period of time.

**Domain:** specific areas within a mine site that share related characteristics.

**Ecological integrity:** the ability of an ecosystem to support and sustain characteristic ecological functioning and

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biodiversity (i.e., species composition and community structure). Ecological integrity can be measured as the extent that a community of native organisms is maintained.

**Ecological restoration:** the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed.

**Ecological restoration program:** a larger composite of many restoration projects.

**Ecological restoration project:** any organized effort undertaken to achieve substantial recovery of a native ecosystem, from the planning stage through implementation and monitoring. A project may require multiple agreements or funding cycles. A project may also be one of many projects in a long-term restoration program.

**Ecosystem:** assemblage of biotic and abiotic components that interact to form complex food webs, nutrient cycles, and energy flows. The term ecosystem is used in the Standards to describe an ecological assemblage of any size or scale.

**Ecosystem attributes:** see Key ecosystem attributes.

**Ecosystem maintenance:** ongoing activities, applied after full or partial recovery, intended to counteract processes of ecological degradation to sustain the attributes of an ecosystem. Higher ongoing maintenance is likely to be required at restored sites where higher levels of threats continue, compared to sites where threats have been controlled.

**Ecosystem resilience:** the degree, manner, and pace of recovery of ecosystem properties after disturbance. In plant and animal communities this property is highly dependent on adaptations by individual species to disturbances or stresses experienced during the species' evolution. See also Social-ecological resilience.

**Ecosystem restoration:** the process of halting and reversing degradation, resulting in improved ecosystem services and recovered biodiversity. Ecosystem restoration encompasses a wide continuum of practices, depending on local conditions and societal choice.

**Ecosystem services:** the direct and indirect contributions of ecosystems to human well-being. They include the production of clean soil, water and air, the regulation of climate and disease, nutrient cycling and pollination, the provisioning of a range of goods useful to humans and potential for the satisfaction of aesthetic, recreation and other human values. These are commonly referred to as supporting, regulation, provisioning, and cultural services. Restoration goals may specifically refer to the reinstatement of particular ecosystem services or the amelioration of the quality and flow of one or more services.

**External exchanges:** the two-way flows that occur between ecological units within the landscape or aquatic environment including flows of energy, water, fire, genetic material, organisms, and propagules. Exchanges are facilitated by habitat linkages.

**Five-star System:** a tool used to identify the level of recovery aspired to by a restoration or rehabilitation project, and to progressively evaluate and track the degree of native ecosystem recovery over time relative to the reference model. This tool also provides a means to report changes from the baseline condition relative to the reference. (Note: this system refers only to the recovery outcomes and not the restoration activities used to attain them.)

**Full recovery:** the state whereby all ecosystem attributes closely resemble those of the reference ecosystem (model). It is preceded by the ecosystem exhibiting self-organization that leads to the full resolution and maturity of ecosystem attributes.

**Functional traits:** morphological, biochemical, physiological, structural, phenological, or behavioral characteristics that are expressed in phenotypes of individual organisms and are considered relevant to the response of such organisms to the environment or their effects on ecosystem properties.

**Functions** (of an ecosystem): the workings of an ecosystem arising from interactions and relationships between biota and abiotic elements. This includes ecosystem processes such as primary production, decomposition, nutrient cycling and transpiration, and properties such as competition and resilience.

**Future Practice:** Where future research results in knowledge, and when applied, improves the effectiveness and efficiency of a restoration project. See also "adaptive management."

**Gene flow:** exchange of genetic material between individual organisms that maintains the genetic diversity of a species' population. In nature, gene flow can be limited by lack of dispersal vectors and by topographic barriers such as mountains and rivers. In fragmented landscapes it can be limited by the separation of remnant habitats. Gene flow between introduced and remnant populations can have negative impacts, such as outbreeding depression or positive impacts such as reduced inbreeding depression.

**Green infrastructure:** a network of natural or seminatural features, for example, wetlands, healthy soils, and forest ecosystems that can help increase ecosystem services.

**Human well-being:** see well-being.

**Indicators** (of recovery): characteristics of an ecosystem that can be used for measuring the progress toward restoration goals or objectives at a particular site (e.g., measures of presence/absence and quality of biotic or abiotic components of the ecosystem).

**Intrinsic value** (of ecosystems and biodiversity): intrinsic value is the value that an entity has in itself, for what it is, or as an end. The contrasting type of value is instrumental value. Instrumental value is the value that something has as a means to a desired or valued end.

**Key ecosystem attributes:** broad categories developed for restoration standards to assist practitioners with evaluating the degree to which biotic and abiotic properties and functions of an ecosystem are recovering. In this document six categories are identified: absence of threats, physical conditions, species composition, structural diversity, ecosystem function, and external exchanges. From the attainment of these attributes emerge complexity, self-organization, resilience, and sustainability.

**Landscape-level flows:** exchanges that occur at a level larger than individual ecosystems or sites (including within aquatic environments) and including flows of energy, water, fire, and genetic material. Flows are facilitated by habitat linkages.

**Landscape restoration:** a planned process that seeks to recover landscape-level ecological integrity and the capacity of

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a landscape to provide long-term, landscape-specific ecosystem services essential for improving human well-being.

**Local ecological knowledge:** knowledge, practices, and beliefs regarding ecological relationships that are gained through extensive personal observation of and interaction with local ecosystems, and shared among local resource users.

**LoM (Life of Mine):** The length of time a mine is, or is planned to be, in production. Based on a mine plan developed in consideration of the available capital and the ore reserves or a reasonable and justifiable extension of the reserve estimate.

**Management** (of an ecosystem): a broad categorization that can include maintenance and repair of ecosystems (including restoration).

**Mandatory restoration:** restoration that is required (mandated) by government, court of law, or statutory authority, which may include some types of biodiversity offsets. In some parts of the world, mandatory restoration is included in compensatory mitigation programs.

**Mitigation Hierarchy:** a tool designed to help limit, as far as possible, the negative impacts of development projects on biodiversity and ecosystem services. It involves a sequence of four key actions—"avoid," "minimize," "restore," and "offset"—and provides a best-practice approach to aid in the sustainable management of living, natural resources by establishing a mechanism to balance conservation needs with development priorities.

**Native ecosystem:** an ecosystem comprising organisms that are known to have evolved locally or have recently migrated from neighboring localities due to changing environmental conditions including climate change. In certain circumstances, traditional cultural ecosystems or semi-natural ecosystems are considered to be native ecosystems. Presence of nonnative species or the expansion of ruderal species in native ecosystems are forms of degradation.

**Native species:** taxa considered to have their origins in a given region or that have arrived there without recent (direct or indirect) transport by humans. Among ecologists, debate exists over how precisely to define this concept.

**Natural capital:** stocks of natural resources that are renewable (ecosystems, organisms), non-renewable (petroleum, coal, minerals, etc.), replenishable (the atmosphere, potable water, fertile soils), and cultivated (landraces, heritage crops, and the know-how attached to them), and from which flow ecosystem services.

**Natural recovery potential:** capacity of ecosystem attributes to recovery at a site through natural regeneration. Degree of this potential in a degraded ecosystem will depend on the extent and duration of the impact and whether the impact resembles those to which the ecosystem's species have adapted over evolutionary time frames. Natural recovery potential needs to be present for the application of natural regeneration or assisted regeneration approaches to ecological restoration.

**Natural restoration:** Term used in China for *natural regeneration approach*.

**Natural regeneration:** germination, birth, resprouting, or other recruitment and growth of biota including plants, animals and microbiota, that does not involve human intervention, whether arising from colonization, dispersal, or in situ processes.

**Natural** (or spontaneous) **regeneration approach:** ecological restoration that relies on increases in desirable individuals and other improvements in ecological conditions following removal of causes of degradation, as distinct from an assisted regeneration approach, which includes interventions to correct abiotic and biotic damage and trigger biotic recovery.

**Nature-based solutions:** actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits.

**Net gain:** Post-mining ecological restoration and recovery achieves a measurable positive improvement in ecosystem integrity, including native biodiversity, and the reinstatement of nature and natural values for society from the pre-mining baseline. Net gain can be achieved within the mine footprint (project scale) or more widely (landscape scale) when improvements extend beyond the mined area after accounting for leakage (spatial shifts in degradation to an area beyond the restoration site). Net gain must be measured at appropriate temporal scales and is applicable at all spatial scales. Net gain is applicable only when the pre-mining ecosystem was in an already degraded state; it is not possible to achieve net gain when mining intact or non-degraded native ecosystems.

**North–South cooperation:** a broad framework for development cooperation between the northern hemisphere or North (predominantly upper-income countries) and the southern hemisphere or South (predominantly lower-income countries) in the political, economic, social, cultural, environmental, and technical domains.

**Offset:** Measurable conservation outcomes, resulting from actions applied to areas not impacted by the project, that compensate for undesirable residual project impacts that cannot be avoided minimized and/or rehabilitated/restored.

**Old-growth ecosystems (including old growth forests):** defined for the MSRS as ecosystems that require long periods to mature (often hundreds of years) and which provide ecosystem services including fauna habitat critical to support threatened wildlife (e.g., nest and denning hollows) and plant habitat that supports threatened epiphytes, succulents, and other conservative and highly specialized plants (e.g., orchids).

**Over-utilization:** any form of harvesting or exploitation of an ecosystem beyond its capacity to regenerate those resources. Examples include over-fishing, over-clearing, over-grazing, and over-burning.

**Partial recovery:** the state whereby some recovery has occurred, but not all ecosystem attributes closely resemble those of the reference model.

**Participatory monitoring:** a system that involves stakeholders from multiple levels in project design and the collection and analysis of data gathered from a given management activity that leads to improved collaborative decision-making.

**PMLU (post-mining land use):** the use of mined lands once active mining is complete.

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**Post-mining baseline:** the environmental characterization of an area once mining has ceased but restorative activities are yet to commence.

**Practitioner:** an individual who applies practical skills and knowledge to plan, implement and monitor ecological restoration tasks at project sites.

**Pre-mining baseline:** the environmental characterization of an area prior the development of a mining project.

**Productivity:** the rate of generation of biomass from the growth and reproduction of plants, animals, and other organisms.

**Progressive restoration:** ecological restoration and allied activities undertaken continually and sequentially during the entire period that a project is active.

**Propagule:** any material that functions in propagating an organism, including larvae, seeds, juveniles, or adults. Propagules are produced by plants, animals, fungi, and other organisms.

**Reclamation:** A broad term used to describe multiple post-mining activities but often relates to the process of reconverting disturbed land to its former or an alternative land use. Also used to describe the formation of productive land from the sea.

**Reconstruction approach:** a restoration approach where arrival of the appropriate biota is entirely or almost entirely dependent upon human agency as they cannot regenerate or recolonize within feasible time frames, even after expert-assisted regeneration interventions.

**Recovery:** the process by which an ecosystem regains its composition, structure, and function relative to the levels identified for the reference ecosystem. In restoration, recovery usually is assisted by restoration activities—and recovery can be described as partial or full.

**Recovery gap:** a physical, biological, or knowledge impediment that cannot be overcome and reflects the discrepancies in biological and functional capacity between the pre-mining state (the baseline and the agreed target “reference” or, the agreed alternate reference) and what is technologically possible given the best endeavors and science to achieve the reference condition.

**Recruitment:** production of a subsequent generation of organisms. Successful recruitment is measured not by numbers of new organisms alone (e.g., not every hatchling or seedling) but by the number that develop as independent, reproductively competent individuals in the population.

**Reference ecosystem:** a representation of a native ecosystem that is the target of ecological restoration (as distinct from a reference site). A reference ecosystem usually represents a non-degraded version of the native ecosystem complete with its flora, fauna, and other biota, abiotic elements, functions, processes, and successional states that might have existed on the restoration site had degradation not occurred, adjusted to accommodate changed or predicted environmental conditions.

**Reference model:** a model that indicates the expected condition that the restoration site would have been in had it not been degraded (with respect to flora, fauna and other biota, abiotic elements, functions, processes, and successional states). This condition is not the historical condition, but rather reflects background and predicted changes in environmental conditions.

**Reference site:** an extant intact site that has attributes and a successional phase similar to the restoration project site and that is used to inform the reference model. Ideally the reference model would include information from multiple reference sites.

**Regeneration:** see Natural regeneration.

**Rehabilitation:** management actions that aim to reinstate a level of ecosystem functioning on degraded sites where the goal is renewed and ongoing provision of ecosystem services rather than the substantial recovery and integrity, including biodiversity, of a designated native reference ecosystem.

**Remediation:** a management activity, such as the removal or detoxification of contaminates or excess nutrients from soil and water, that aims to remove sources of degradation.

**Repurposing:** Beneficial reuse of a closed mining operation, whether through value-added reuse of the land (e.g., energy generation or residential), reuse of infrastructure at another site, or derivative business opportunities to create positive economic activity.

**Resilience:** see Ecosystem resilience and Social-ecological resilience.

**Restoration:** see Ecological restoration.

**Restoration ecology:** the branch of ecological science that provides concepts, models, methodologies, and tools for the practice of ecological restoration. It also benefits from direct observation of and participation in restoration practice.

**Restoration activities:** any action, intervention, or treatment intended to promote the recovery of an ecosystem or component of an ecosystem, such as soil and substrate amendments, control of invasive species, habitat conditioning, species reintroductions, and population reinforcements.

**Restorative activities:** activities (including ecological restoration) that reduce degradation or improve conditions for the partial or full recovery of ecosystems. These are sometimes described as a “family” of interrelated restorative activities.

**Restorative continuum:** a spectrum of activities that directly or indirectly support or attain at least some recovery of ecosystem attributes that have been lost or impaired.

**Revegetation:** establishment, by any means, of plants on sites (including terrestrial, freshwater, and marine areas) that may or may not involve local or native species.

**Self-organizing:** a state whereby all the necessary elements are present, and the ecosystem’s attributes can continue to develop toward the appropriate reference state without human assistance. Self-organization is evidenced by patterns and processes such as growth, reproduction, ratios between producers, herbivores, and predators and niche differentiation, relative to characteristics of the reference ecosystem. It does not readily apply to the restoration of traditional cultural ecosystems, semi-natural ecosystems, or severely degraded or damaged ecosystems such as mine sites.

**Semi-natural ecosystem:** In the European Union (EU) legal context, biodiverse, stable ecological assemblages created by human activities (e.g., grazed or mowed alpine meadows) that have evolved under traditional agricultural, pastoral, or other

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human management. They can be centuries old and depend on traditional management for their characteristic composition, structure, and function. These ecosystems are highly valued for their biodiversity and ecosystem services, and can be a reference for ecological restoration. Examples include alpine and lowland meadows, heathlands, chalk grasslands, coppice forests, wood pastures, and grazing marshes. They differ from "cultural ecosystems," as defined by the EU, created to provide ecosystem services, but that result in degraded ecosystems with lower biodiversity values. Examples of the latter include arable fields, species-poor agricultural grasslands, mineral extraction areas, and urban landscapes with city parks. They are not appropriate as a reference for ecological restoration, but can be the starting point for ecological restoration or rehabilitation. In this sense, semi-natural ecosystem has roughly the same meaning as high-quality traditional cultural ecosystems in the MSRS.

**Site:** discrete area or location. Can occur at different scales but is generally at the patch or property scale (i.e., smaller than a landscape).

**South–South cooperation:** a broad framework for collaboration among countries of the Southern Hemisphere in the political, economic, social, cultural, environmental, and technical domains. Involving two or more developing countries, it can take place on a bilateral, regional, subregional, or interregional basis. See also Triangular Cooperation.

**Social-ecological resilience:** the capacity of a complex social-ecological system to absorb disturbance and reorganize while undergoing change such that it retains similar function, structure, identity, and feedbacks. It is a measure of the extent to which a complex social-ecological system can adapt and persist in the face of threats and stresses.

**Social-ecological system:** complex, integrated and linked systems of people and Nature, emphasizing that humans are a part of nature.

**Spatial patterning:** the spatial structure of ecosystem components (in vertical or horizontal plane) that arises due to differences in substrate, topography, hydrology, vegetation, disturbance regimes, or other factors.

**Species:** used here as a generic term to represent a species or intraspecific taxon, even if not formally described by science.

**Stakeholders:** the people and organizations who are involved in or affected by an action or policy and can be directly or indirectly included in the decision-making process; in environmental and conservation planning, stakeholders typically include governmental and non-governmental agencies, businesses, scientists, landowners and rights holders, Indigenous people, and local communities.

**Stepwise ecological restoration:** integration of three restorative modes that can be used with different levels of ecosystem degradation: environmental remediation for seriously degraded ecosystems, ecological rehabilitation for moderately degraded ecosystems, and ecological (even natural) restoration for slightly degraded ecosystems.

**Stratum, strata:** vegetation layer or layers in an ecosystem; often referring to vertical layering such as trees, shrubs, and herbaceous layers.

**Substrate:** the soil, sand, rock, shell, debris or other medium where organisms grow and ecosystems develop.

**Substantial recovery:** the level of recovery aimed for if a project is to be called an ecological restoration project. This level of recovery cannot be tightly linked to a particular recovery metric (although a mid-point recovery level, would be a reasonable minimum criterion) because the value of a restoration project can be influenced by the ecological importance of the ecosystem and the scale of the project.

**Successional:** referring to the process or pattern of replacement or development of an ecosystem after disturbance.

**Target:** an element of biodiversity (species, habitat, or ecological system) at a project site on which a project has chosen to focus. All targets should collectively represent the biodiversity of concern at the site. Human well-being (or social) targets focus on those components of human well-being affected by the status of conservation targets and associated ecosystem services, or the restoration process itself.

**Threat:** a human activity or other factor that directly or indirectly degrades one or more targets.

**Threshold** (ecological): a point at which a small change in environmental or biophysical conditions causes a shift in an ecosystem to a different ecological state. Once one or more ecological thresholds have been crossed, an ecosystem may not easily return to its previous state or trajectory without major human interventions, or at all if the threshold is irreversible.

**Traditional cultural ecosystems:** ecosystems that have developed under the joint influence of natural processes and human-imposed organization to provide composition, structure, and functioning more useful to human exploitation. Those considered high-quality examples of native ecosystems can function as reference models for ecological restoration, whereas others converted primarily to nonnative species or are otherwise degraded do not function as reference models for ecological restoration. See also Semi-natural ecosystem.

**Traditional ecological knowledge:** knowledge and practices learned from experience and observation, and passed from generation to generation informed by strong cultural memories, sensitivity to change, and values that include reciprocity.

**Trajectory** (ecological): a course or pathway of an ecosystem's condition (i.e., structure and function) over time. It may entail degradation, stasis, adaptation to changing environmental conditions, or response to ecological restoration—ideally leading to recovery of lost integrity and resilience.

**Triangular cooperation:** collaboration in which traditional donor countries and multilateral organizations facilitate South–South initiatives through the provision of funding, training, management, and technological systems as well as other forms of support.

**Trophic levels:** stages in food webs (e.g., producers, herbivores, predators, and decomposers).

**Well-being:** a context- and situation-dependent state of humans, comprising basic material for a good life, freedom and choice, health, good social relations, and security.

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## Supporting Information

The following information may be found in the online version of this article:

**Appendix S1** Case studies.
**Appendix S2**. Pertinent issues and explanatory concepts.
**Appendix S3**. Blank Social Benefits and Ecological Recovery Wheels.

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