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SER SOCIETY FOR ECOLOGICAL RESTORATION

POLICY ARTICLE

International principles and standards for the practice of ecological restoration. Second edition

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EXECUTIVE SUMMARY

Ecological restoration, when implemented effectively and sustainably, contributes to protecting biodiversity; improving human health and wellbeing; increasing food and water security; delivering goods, services, and economic prosperity; and supporting climate change mitigation, resilience, and adaptation. It is a solutions-based approach that engages communities, scientists, policymakers, and land managers to repair ecological damage and rebuild a healthier relationship between people and the rest of nature. When combined with conservation and sustainable use, ecological restoration is the link needed to move local, regional, and global environmental conditions from a state of continued degradation, to one of net positive improvement. The second edition of the *International Principles and Standards for the Practice of Ecological Restoration* (the Standards) presents a robust framework for restoration projects to achieve intended goals, while addressing challenges including effective design and implementation, accounting for complex ecosystem dynamics (especially in the context of climate change), and navigating trade-offs associated with land management priorities and decisions.

The Standards establish eight principles that underpin ecological restoration. Principles 1 and 2 articulate important foundations that guide ecological restoration: effectively engaging a wide range of stakeholders, and fully utilizing available scientific, traditional, and local knowledge, respectively. Principles 3 and 4 summarize the central approach to ecological restoration, by highlighting ecologically appropriate reference ecosystems as the target of restoration and clarifying the imperative for restoration activities to support ecosystem recovery processes. Principle 5 underscores the use of measurable indicators to assess progress toward restoration objectives. Principle 6 lays out the mandate for ecological restoration to seek the highest attainable recovery. Tools are provided to identify the levels of recovery aspired to and to track progress. Principle 7 highlights the importance of restoration at large spatial scales for cumulative gains. Finally, ecological restoration is one of several approaches that address damage to ecosystems and Principle 8 clarifies its relationships to allied approaches on a "Restorative Continuum".

The Standards highlight the role of ecological restoration in connecting social, community, productivity, and sustainability goals. The Standards also provide recommended performance measures for restorative activities for industries, communities, and governments to consider. In addition, the Standards enhance the list of practices and actions that guide practitioners in planning, implementation, and monitoring activities. The leading practices and guidance include discussion on appropriate approaches to site assessment and identification of reference ecosystems, different restoration approaches including natural regeneration, consideration of genetic diversity under climate change, and the role of ecological restoration in global

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restoration initiatives. This edition also includes an expanded glossary of restoration terminology. SER and its international partners produced the Standards for adoption by communities, industries, governments, educators, and land managers to improve ecological restoration practice across all sectors and in all ecosystems, terrestrial and aquatic. The Standards support development of ecological restoration plans, contracts, consent conditions, and monitoring and auditing criteria. Generic in nature, the Standards framework can be adapted to particular ecosystems, biomes, or landscapes; individual countries; or traditional cultures. The Standards are aspirational and provide tools that are intended to improve outcomes, promote best practices, and deliver net global environmental and social benefits. As the world enters the UN Decade on Ecosystem Restoration (2021–2030), the Standards provide a blueprint for ensuring ecological restoration achieves its full potential in delivering social and environmental equity and, ultimately, economic benefits and outcomes.

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Section 1 — Introduction

The International Principles and Standards for the Practice of Ecological Restoration (the Standards) provide a guide to practitioners, operational personnel, students, planners, managers, regulators, policymakers, funders, and implementing agencies involved in restoring degraded ecosystems across the world—whether terrestrial, freshwater, coastal, or marine. They place ecological restoration into a global context, including its role in recovering biodiversity and improving human **wellbeing**[1] in times of rapid global change.

Ecological Restoration as a Means of Improving Biodiversity and Human Wellbeing and Its Role in Broader Global Initiatives

Humanity recognizes the planet's **native ecosystems** as having irreplaceable ecological, societal, and economic value. In addition to their **intrinsic value**, such as **biodiversity** and spiritual or aesthetic importance, healthy native ecosystems assure the flow of **ecosystem services**. These services include: provision of clean water and air, healthy soils, culturally important artifacts, and the food, fiber, fuel, and medicines essential for human health, wellbeing, and livelihoods. Native ecosystems can also reduce the effects of natural disasters and mitigate accelerated climate change. Ecosystem degradation, damage, and destruction (hereafter, collectively referred to as **degradation**) diminish the biodiversity, functioning, and **resilience** of ecosystems, which in turn negatively affects the resilience and sustainability of **social–ecological systems**. Although protecting remaining native ecosystems is critical to conserving the world's natural and cultural heritage, protection alone is insufficient, given past and current degradation. To respond to current global environmental challenges and to sustain the flow of ecosystem services and goods essential for human wellbeing, ***global society must secure a net gain in the extent and functioning of native ecosystems by investing not only in environmental protection, but also in environmental repair including ecological restoration***. This repair must be implemented at multiple scales to achieve measurable effects worldwide.

Awareness of the need for environmental repair is growing, resulting in a global escalation of ecological restoration and related efforts (see also Section 4, Part 3). For example, the United Nations (UN) Sustainable Development Goals (SDGs) for 2030 call for restoration of marine and coastal ecosystems (Goal 14) and terrestrial ecosystems (Goal 15) that have been degraded to "*protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss*." The Convention on Biological Diversity (2016) calls for the "*restoration of degraded natural and semi-natural ecosystems, including in urban environments, as a contribution to reversing the loss of biodiversity, recovering connectivity, improving ecosystem resilience, enhancing the provision of ecosystem services, mitigating and adapting to the effects of climate change, combating desertification and land degradation, and improving human well-being while reducing environmental risks and scarcities*." And, the United Nations General Assembly has declared 2021–2030 the "Decade on Ecosystem Restoration." The concept of restoration in many of these initiatives and agreements is very broad and includes many approaches to **ecosystem management** and **nature-based solutions**, all of which are valuable. The Standards address the relationship between ecological restoration and other ecosystem management and nature-based solutions, and clarify the specific role of ecological restoration in contributing to the goals of conserving biodiversity and improving human wellbeing worldwide.

Need for Principles and Standards

Repairing degraded ecosystems is a complex task requiring significant time, resources, and knowledge. Ecological restoration contributes in substantial ways to protecting biodiversity and human wellbeing, but many restoration projects and programs, however well intentioned, have underperformed. The Standards recognize that appropriate design; good planning and implementation; sufficient knowledge, skill, effort and resources; understanding of specific social contexts and risks; appropriate stakeholder involvement; and adequate monitoring for adaptive management will contribute to improved outcomes. Application of principles and standards can increase effectiveness of ecological restoration efforts by establishing criteria for technical implementation across different ecosystem types. They also provide a framework that engages stakeholders and respects socio-cultural realities and needs, which can be applied to both mandatory (i.e. required as part of consent conditions) and non-mandatory restoration (i.e. the voluntary repair of damage). These criteria can improve ecological restoration outcomes, whether used to guide agencies, companies, or individuals engaged in planning, implementation, and monitoring; to guide regulators in developing agreements for mandatory restoration and evaluating whether those agreements have been met; or to guide policymakers in designing, supporting, funding, and evaluating restoration projects at any scale. Thus, the use of clear and carefully considered principles and standards underpinning ecological restoration can reduce the risk of unintended damage to ecosystems and native biodiversity, and help to develop high-quality projects and programs amenable to monitoring and assessment.

Background

This document expands upon and joins SER's collection of foundation documents including the *SER International Primer on Ecological Restoration* (SER 2004), *Guidelines for Developing and Managing Restoration Projects* (Clewell et al. 2005), *Ecological Restoration—a Means of Conserving Biodiversity and Sustaining Livelihoods* (Gann & Lamb 2006), and *Ecological Restoration for Protected Areas: Principles, Guidelines and Best Practices* (Keenleyside et al. 2012). It also utilizes SER's *Code of Ethics* (SER 2013) and specifically draws on

[1]Terms in boldface are defined in the Glossary section.

material and models in the two editions of *National Standards for the Practice of Ecological Restoration in Australia* (McDonald et al. 2016*a*, 2018). Several books were influential including *Restoration Ecology: The New Frontier* (Van Andel & Aronson 2012), *Ecological Restoration: Principles, Values and Structure of an Emerging Profession* (Clewell & Aronson 2013), *Foundations of Restoration Ecology* (Palmer et al. 2016), *Routledge Handbook of Ecological and Environmental Restoration* (Allison & Murphy 2017), and *Management of Ecological Rehabilitation Projects* (Liu & Clewell 2017). We have drawn content from the editorial *Ecosystem Restoration is Now a Global Priority* (Aronson & Alexander 2013), and the policy documents *Ecosystem Restoration: Short-term Action Plan* of the CBD (Convention on Biological Diversity 2016), *Partnering with Nature: The Case for Natural Regeneration in Forest and Landscape Restoration* (Chazdon et al. 2017), and *Restoring Forests and Landscapes: The Key to a Sustainable Future* by the Global Partnership on Forest and Landscape Restoration (GPFLR; Besseau et al. 2018). Works published in SER's journal *Restoration Ecology*, book series on *The Science and Practice of Ecological Restoration* (Island Press), and Restoration Resource Center, as well as many other documents have informed development of this edition. While Sections 1 through 3 are mostly free of references for brevity's sake, Section 4 (Leading Practices), Appendix 1, and Supplement S1 include citations.

What Is New in This Version?

To better address the diverse roles people play in restoration and how the goals of Indigenous groups fit into the overall picture of ecological restoration, we have reorganized the Principles to better incorporate social-economic and cultural factors that can greatly affect outcomes of restoration. Principle 1 expands on social goals and includes a "Social Benefits Wheel" tool to help convey social targets and goals of a project.

Principles and Key Concepts are merged into a single section on Principles. A compilation of historical documents used to synthesize the Principles is provided in Supplement S1. Scaling-up ecological restoration and the relationship between ecological restoration and allied activities included in Section 4 of the first edition are incorporated into Principles 7 and 8 in this version.

Key topics related to reference models and restoration approaches are included in a new section on Leading Practices (Section 4), which also considers integration of ecological restoration into global restoration initiatives. We added a technical appendix on sourcing of seeds and other propagules for restoration.

Key Definitions and Terms

SER defines **ecological restoration** as the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed. It 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 and evolution of its component species.

Ecological restoration is commonly used to describe both the process and the outcome sought for an ecosystem, but the Standards reserve the term **restoration** for the *activity* undertaken and **recovery** for the *outcome* sought or achieved. The Standards define ecological restoration as any **activity** with the goal of achieving substantial ecosystem recovery relative to an appropriate **reference model**, regardless of the time required to achieve recovery. Reference models used for ecological restoration projects are informed by **native ecosystems**, including many **traditional cultural ecosystems** (see Principle 3).

Ecological restoration projects or programs include one or more **targets** that identify the native ecosystem to be restored (as informed by the reference model), 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, species composition, community structure, physical conditions, ecosystem function, and external exchanges. Where lower levels of recovery are planned or occur due to resource, technical, environmental, or social constraints, recovery is referred to as **partial recovery**. An **ecological restoration project** or program should aspire to **substantial recovery** of the native biota and ecosystem functions (contrast with **rehabilitation** below). When full recovery is the goal, an important benchmark is when the ecosystem demonstrates **self-organization**. At this stage, if unexpected **barriers** or lack of particular species or processes take recovery off course, further restoration actions may be required to ensure that the trajectory ultimately continues toward full recovery. Once fully recovered, any ongoing activities (e.g. to maintain **disturbance regimes**) would be considered **ecosystem maintenance** or management. Specific activities, such as prescribed fire or the control of invasive species, may be used in both restoration and maintenance phases of a project.

The goal of **rehabilitation** projects is not native ecosystem recovery, but rather reinstating a level of ecosystem functioning for renewed and ongoing provision of ecosystem services potentially derived from nonnative ecosystems as well. Rehabilitation is one of many **restorative activities** aligned along a continuum that includes ecological restoration and its allied and complementary activities, all of which contribute to improving **ecosystem integrity** and **social–ecological resilience** (see Principle 8).

Underpinning Assumptions

A few assumptions about the role of ecological restoration underpin the Standards. First, restoration of most native ecosystems is a challenging process, and substantial recovery usually requires long periods of time. Consequently, many ecological restoration projects are still far from achieving the

levels of biodiversity, ecosystem functioning, and delivery of services of intact ecosystems. Thus, while compensation may be mandated as a result of ecosystem loss or degradation, the ***potential for ecological restoration should never be invoked as a justification for destroying or damaging existing native ecosystems or for unsustainable use***. Similarly, any potential to translocate rare species should not be used to justify destruction of existing intact habitat. Where compensation is mandated, however, the level of compensation should be far in excess of the estimated ecosystem loss or degradation, and care should be exercised to ensure offsets do not cause additional degradation.

Second, the Standards clarify the use of a native reference ecosystem as a model for the ecosystem being restored. The reference model, derived from multiple sources of information, aims to characterize the condition of the ecosystem as it would be had it not been degraded, adjusted as necessary to accommodate changed or predicted change in biotic or environmental conditions (e.g. climate change). The Standards also make clear that appropriate reference models for ecological restoration are not based on immobilizing an ecological community at some past point in time, but rather *increasing potential for native species and communities to recover and continue to reassemble, adapt, and evolve*.

Finally, ecological restoration is part of a larger set of ecosystem management practices designed to conserve and, where appropriate, sustainably utilize native ecosystems. These practices range from regenerative agriculture, fisheries, and forestry to ecological engineering, including those invoked in the Convention on Biological Diversity, the United Nations 2030 Sustainable Development Goals, and by Forest Landscape Restoration (FLR) projects and a multitude of local and regional programs. As such, *ecological restoration complements other conservation activities and nature-based solutions* and vice versa.

Section 2 — Eight Principles that Underpin Ecological Restoration

The following Principles provide a framework to explain, define, guide, and measure the activities and outcomes of ecological restoration practice (Fig. 1). They represent a distillation of principles and concepts presented in SER foundational documents, scientific literature, and practitioner experience (Appendix S1).

Principle 1. Ecological Restoration Engages Stakeholders

Ecological restoration is undertaken for many reasons including to recover **ecosystem integrity** and to satisfy personal, cultural, social-economic, and ecological values. This combination of ecological and social benefits can lead to improved **social–ecological resilience**. Humans benefit from a closer and reciprocal engagement with nature. Participating in restoration projects can be transformative, for example, when children involved in restoration projects develop personal ownership over restoration sites, or when community volunteers seek new career or vocational paths in restoration practice or science. Communities located within or near degraded ecosystems may gain health and other benefits from restoration that improves the quality of air, land, water, and habitats for native species. Indigenous peoples and local communities (both rural and urban)

Figure 1. Eight principles for ecological restoration. Each principle is fully developed in the text.

benefit where restoration reinforces nature-based cultures, practices, and livelihoods (e.g. subsistence fishing, hunting, and gathering). In addition, restoration can provide short-term and long-term employment opportunities for local **stakeholders**, creating positive ecological and economic feedback loops.

Stakeholders can make or break a project. Recognizing the expectations and interests of stakeholders and directly involving them is key to ensuring that both nature and society mutually benefit. Stakeholders can help prioritize distribution of restoration actions across the landscape, set project goals

Table 1. Sample social five-star system for evaluating progress toward social goals in a restoration project or program. Social goals will 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.

Attribute	★	★★	★★★	★★★★	★★★★★
Stakeholder engagement	Stakeholders identified and made aware of project and its rationale. Ongoing communication strategy prepared	Key stakeholders supportive and involved in project planning phase	Number of stakeholders, support, and involvement increasing at start of implementation phase	Number of stakeholders, support, and involvement consolidating throughout implementation phase	Number of stakeholders, support, and involvement optimal, and self-management and succession arrangements are in place
Benefits distribution	Benefits to local communities negotiated, ensuring equitable opportunities and reinforcement of traditional cultural relationships to the site	Benefits to local communities starting and equitable opportunities maintained. Traditional cultural elements integrated, as appropriate, into project planning	Benefits to locals at an intermediate level and equitable opportunities maintained. Any traditional cultural elements well secured within project implementation	Benefits to locals at a high level and equitable opportunities maintained. Substantial integration of any traditional cultural elements, increasing reconciliation prospects	Benefits to locals and equitable opportunities very high, with optimal integration of any traditional cultural elements, substantially contributing to reconciliation and social justice
Knowledge enrichment	Relevant sources of existing knowledge identified and mechanisms for generating new knowledge selected	Relevant sources of existing knowledge (and potential for new knowledge) informing project planning and monitoring design	Implementation phase making use of all relevant knowledge, stakeholder feedback, and early project results	Implementation enriched by all relevant knowledge as well as from trial and error arising from the project itself; results analyzed and reported	Implementation enriched by all 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 budget)	Land and water management systems resulting in high level recovery and conservation of natural capital (including carbon neutral status)	Land and water management systems resulting in very high level of recovery and conservation of natural capital (including carbon 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 in testing phase	Trials of Sustainable business and employment models showing success	Sustainable business and employment models with strong levels of success
Community wellbeing	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	Public identification of the site as having wellbeing benefits from local participation and return of ecosystem services including recreation

(including desired level of recovery), contribute knowledge about ecological conditions and successional patterns to improve development of reference models, and engage in **participatory monitoring**. Additionally, stakeholders can provide political and financial support for long-term project sustainability, as well as moderating conflicts or disagreements that may arise. Recognition of diverse forms of property ownership and management (e.g. government, private, communal), land tenure, and social organization is essential to accomplish these goals. Managers of restoration projects should, therefore, genuinely and actively engage with those who live or work within or near restoration sites, and those who have a stake in the project's ecological values and **natural capital** (including ecosystem services). Ideally, this engagement should occur at the conceptual phase or well ahead of project initiation, so stakeholders can help define the vision, targets, goals, objectives, and methods of implementation and monitoring. Engagement should continue throughout the project to help meet social expectations, build capacity and a sense of ownership, and maintain support and input. Collaboratively building dialogue and trust among all stakeholders fosters respect for different viewpoints and knowledge types and maintains interest and commitment during all phases of the project. Such collaboration can lead to more rapid and effective local decision-making, particularly when participatory or collaborative monitoring approaches are implemented.

Collaborating with local communities, including Indigenous communities, nonprofit citizen groups, and citizen scientists, to develop restoration plans can increase community investment in restoration. Youth and women, particularly in under served communities, can become powerful ambassadors. Such community engagement may bring social justice and human ecology components to a project, and can help leverage funding.

Social and human **wellbeing** goals, including those that reinstate or reinforce ecosystems services, must be identified alongside ecological goals during the planning stage of a restoration project (see Principle 5, Principle 7, and Section 4, Part 3). Guidance for identifying appropriate goals to improve both social and environmental outcomes in social–ecological systems is provided in a range of documents (e.g. Lynam et al. 2007; Keenleyside et al. 2012; REDD+ SES 2012; Conservation Measures Partnership 2013). Example templates for communicating progress toward social goals are provided in Table 1 and Fig. 2. These templates can be adapted to suit the social goals of any project.

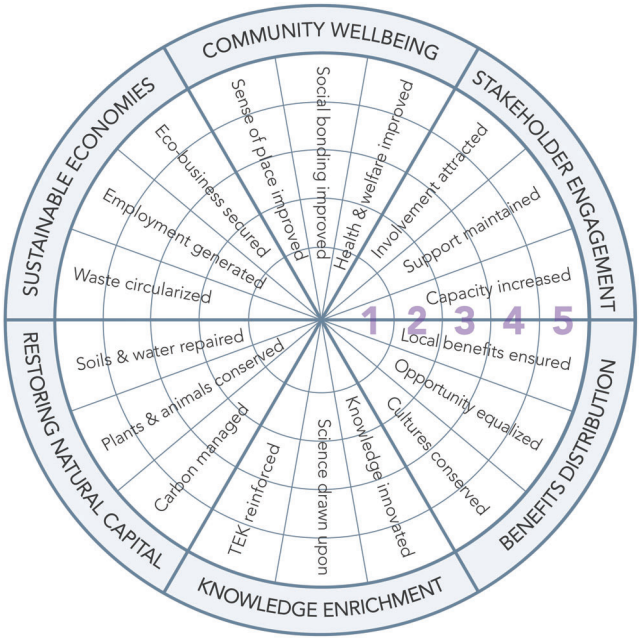

Figure 2. Example of a social benefits wheel to assist in tracking the degree to which an ecological restoration project or program is attaining its social development targets and goals. This and Table 1 can be customized to suit the specific targets and goals of any ecological restoration project or program. It complements the ecological recovery wheel used to evaluate ecological recovery progress compared to the project's reference model and introduced in PRINCIPLE 6. For symmetry of design, six attributes and three sub-attributes are used in this example, but there may be more or fewer needed depending on the project.

Principle 2. Ecological Restoration Draws on Many Types of Knowledge

The practice of ecological restoration requires a high degree of ecological knowledge that can be drawn from **practitioner** experience, **Traditional Ecological Knowledge, Local Ecological Knowledge** (Box 1), and **scientific discovery**. These forms of knowledge are the product of observation, experimentation, and trial and error, whether formal or informal. The best available knowledge should inform the design and implementation of ecological restoration, and contribute to **adaptive management** (Principle 5), whereby the results of restoration treatments can indicate the need to modify management approaches.

Practitioner knowledge is derived from experience in repairing ecosystems, and from information from a spectrum of disciplines (e.g. restoration ecology, agronomy and seed production, forestry, horticulture, botany, wildlife science, zoology, hydrology, soil science, engineering, landscape design, conservation biology, and natural resource management). Additionally, LEK and TEK experts, who are typically members of a local community, can provide extensive and detailed information about sites and ecosystems drawn from their long-term relationships and connections to these sites. When integrated into restoration projects, these multiple forms of knowledge provide opportunities to improve restoration outcomes for ecological, social, and cultural benefits.

Scientific knowledge is generated through the process of systematic measurement and hypothesis testing. Restoration-relevant scientific knowledge comes from basic and applied research within a wide range of disciplines from economics to the social, physical, and biological sciences including the sub-disciplines of restoration ecology, conservation biology, conservation genetics, and landscape ecology. While such knowledge provides information essential to

Box 1. Traditional ecological knowledge and its relevance to ecological restoration.

Traditional Ecological Knowledge (TEK) is defined as knowledge and practice passed on from generation to generation and informed by strong cultural memories, sensitivity to change, and values that include reciprocity. Examples of TEK land-care include using prescribed fire and seasonal flooding to modify vegetation, and conserving ecosystem engineers (e.g. beavers and elephants) or apex predators (e.g. wolves and lions) to improve habitat for other species and in turn, food resources for humans. These processes function within the range of natural variability for an ecosystem. Indigenous people have used such practices over millennia to increase ecosystem productivity of food, raw materials for medicine, and ceremonial items. TEK involves reciprocity—sharing and restraint sustained by spiritual beliefs that regard plants and animals as human kin. TEK practices increase biodiversity and improve ecological resilience by creating fine-grained, landscape mosaics. TEK observations are qualitative and long-term. Observers are often people engaged in subsistence practices including hunting, fishing, and gathering. Their survival is linked to the health of the land. Most importantly, TEK is inseparable from a culture's spiritual and social fabric. In the Indigenous worldview, it takes all of what it means to be human—body, mind, heart, and spirit—to understand something ecologically. Consequently, TEK offers important ecological insights, but also a web of knowledge that includes values that can help restore ecosystems.

Local Ecological Knowledge (LEK) is defined as local, place-based knowledge of the land and its processes applied by humans to create more productive lands and healthier ecosystems, increasing biodiversity and improving ecosystem resilience. LEK is prevalent in places where Indigenous people do not have a presence and in which knowledge of Indigenous practices has been lost. Widespread in Europe, for example, LEK includes pre-Industrial Era farming, water management, and subsistence hunting practices. In some places, both LEK and TEK can function together, although they may come from different cultural paradigms.

By incorporating TEK or LEK in ecological restoration, practitioners can rapidly identify and assess species and their suitability, successional processes and stages, and key species interactions. Further, TEK and LEK can help to define native reference ecosystems and catalyze restoration by allowing application of cultural practices such as prescribed fire, rotational grazing, and water management. Ecological restoration strategies that incorporate formal science, TEK, and LEK may be particularly effective in repairing degraded ecosystems.

design and implement ecological restoration projects, there are significant gaps in understanding of the efficacy (extent that goals and objectives are achieved) and effects (biotic and abiotic responses to management treatments) of many restoration activities, ecological responses to climate change, and improving **climate readiness** (see also Principle 3 and Appendix 1). Scientific research can contribute to closing these gaps. In addition, scientific assessments of ecological restoration practice can address essential ecological questions, such as how ecosystems assemble and function, as well as social–ecological questions. Generating new scientific knowledge may not be necessary or realistic in all ecological restoration projects, but should always be considered, especially when little is known about treatment efficacy or where restoration interventions are extreme or highly risky (e.g. ecosystem reconstruction after mining).

Practitioner-researcher collaborations can enhance scientific endeavors by allowing for powerful experimental designs and improved ability to make inferences from assessments. Such research can increase innovation and provide additional guidance for management. Focused research can help practitioners overcome otherwise intractable problems (e.g. harsh substrate conditions, low reproduction rates, and inadequate supply and quality of germplasm; see Appendix 1). Additionally, the results can be shared and help to lower costs of other projects. Practitioners and local-knowledge experts can play an important role in large-scale research projects by providing access to projects, identifying bottlenecks in capacity and gaps in information, and contributing logistical expertise.

Sharing practical and scientific knowledge is key to implementing restoration efficiently and effectively, and to achieving restoration at scale. An important way to advance the science and practice of large-scale ecological restoration is to develop and promote bilateral and multilateral cooperation among and within countries (see also Section 4, Part 3). Experience and expertise sharing, co-financing, and co-development of new knowledge for more effective policy and practice should be encouraged among regions, and **south–south cooperation** is especially important for knowledge sharing in developing and newly industrialized countries.

Availability of scientific data on the efficacy and effects of restoration treatments should be determined at the project proposal stage. Where technical challenges arise during a **mandatory restoration** project, targeted research should be undertaken to identify alternative restoration interventions within reasonable time frames. If such research still fails to provide solutions, alternative approaches to satisfying legal requirements should be planned.

Lack of progress toward restoration objectives does not mean that restoration is not technically, practically, or economically feasible in the future. Lack of knowledge and technical competency may be overcome through adaptive management, linked to focused, outcome-based monitoring. However, in mandatory restoration (e.g. mining sector), knowledge and capacity should be acquired ahead of the project to ensure that legal agreements can be fulfilled.

Principle 3. Ecological Restoration Practice Is Informed by Native Reference Ecosystems, while Considering Environmental Change

Ecological restoration requires identifying the **native ecosystem** to be restored and developing **reference models** for

Box 2. Reference ecosystems and climate change.

Continuous change in climate over millennia, centuries, and decades is an important characteristic of our planet. Although this backdrop of environmental change is constant, anthropogenically induced climate change has increased the pace of change in many ecosystems worldwide. While these changes are generally recognized as undesirable and require urgent action by society, anticipated changes are likely to be irreversible for the foreseeable future. This means that, alongside working to improve potential for restoration and other actions to slow climate change, climate change needs to be recognized as part of the current environmental background condition to which many species will either adapt or go extinct.

Climate change necessitates target-setting informed by ongoing research on related anticipated effects on species and ecosystems. While uncertainty exists, we know that species turnover and community reassembly under climate change will result in large shifts in entire ecosystems in many geographic areas (e.g. many marine, coastal, alpine, and cool-temperate communities), although in some climatically buffered ecosystems changes may be minimal. As climate changes, climatic envelopes for individual species will shift spatially. This means for a given ecosystem, some species will be lost, while others may survive due to plasticity or ability to adapt to changes in environmental conditions, and still others will newly arrive.

Land degradation, particularly fragmentation, exacerbates climate-change effects on many species and ecological communities, both by isolating populations, which adversely affects genetic diversity and adaptation potential, and by limiting opportunities for species to disperse or migrate to climate-suitable habitats. Because of this, there is a need for management interventions that optimize genetic diversity and potential for populations to adapt, to prevent extirpations from current habitat areas, and that promote migration to new areas. Options include retaining and **augmenting** genetically diverse populations of existing native floral and faunal species, and ensuring that these populations exist in configurations that increase linkages and improve gene flow where appropriate to boost adaptability to changed conditions (see Appendix 1).

Box 3. What about cases where there has been insurmountable environmental change?

Project managers may adopt alternative native ecosystems as targets for areas that are affected by substantial and insurmountable environmental change. Alternative ecosystems would be expected to occur under the changed conditions. Examples of conversion include sites where: (1) hydrology has shifted irreversibly from saline to freshwater (e.g. due to changing stream flows), freshwater to saline (e.g. due to sea level rise), or mesic to arid (e.g. due to lowering water tables or complete dry-downs of rivers or lakes); (2) stormwater has produced intermittent streams; and (3) nutrients have been added to soils and cannot be removed without extreme effort or resources. An alternative reference ecosystem may also be chosen when traditional fire regimes or other ecosystem functions have been irreversibly altered.

Deciding when an alternative reference ecosystem is appropriate is dependent on local conditions and the case for irreversibility, and requires skilled ecological judgment (Fig. 3). More than one alternative reference ecosystem may be appropriate, for example, in urban and highly modified agricultural areas, and careful selection is necessary to match the local social–ecological situation. Additionally, appearance of a site may not be a reliable indicator of restoration potential. In many cases where restoration was assumed by some to be impossible, recovery was achieved after application of skilled and informed approaches. 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 to determine efficacy. Trial treatments are best designed as collaborations between scientists and practitioners, and can help inform the appropriate choice of an ecosystem to use as the basis for developing the reference model.

planning and communicating a shared vision of project **targets** and goals. Reference models should be based on specific real-world ecosystems that are the targets of conservation and restoration activities (e.g. boreal forest, freshwater marsh, coral reef). Optimally the reference model describes the approximate condition the site would be in had degradation not occurred. This condition is not necessarily the same as the historic state, as it accounts for the inherent capacity of ecosystems to change in response to changing conditions. In some instances, the impacts of rapid environmental changes and the capacity for adaptation to these changes may warrant consideration of adjusted or alternative models (see also Boxes 2 & 3 and Section 4, Part 1).

Reference models are developed using multiple sources of information. Best practice is to build empirical models based on information on specific ecosystem attributes obtained from multiple modern analogs or **reference sites**. These sites are environmentally and ecologically similar to the project site, but optimally have experienced little or minimal degradation (but see Box 4). Information on past and current conditions at the site as well as consultation with stakeholders can assist in developing reference models, especially where nondegraded local reference sites are unavailable. This information is usually collected during the site assessment or **baseline inventory** phase of the project (Principle 5)

Reference sites may be rare in regions that have few protected areas. In those situations, previously damaged sites that have had varying amounts of time for natural recovery (e.g. new protected

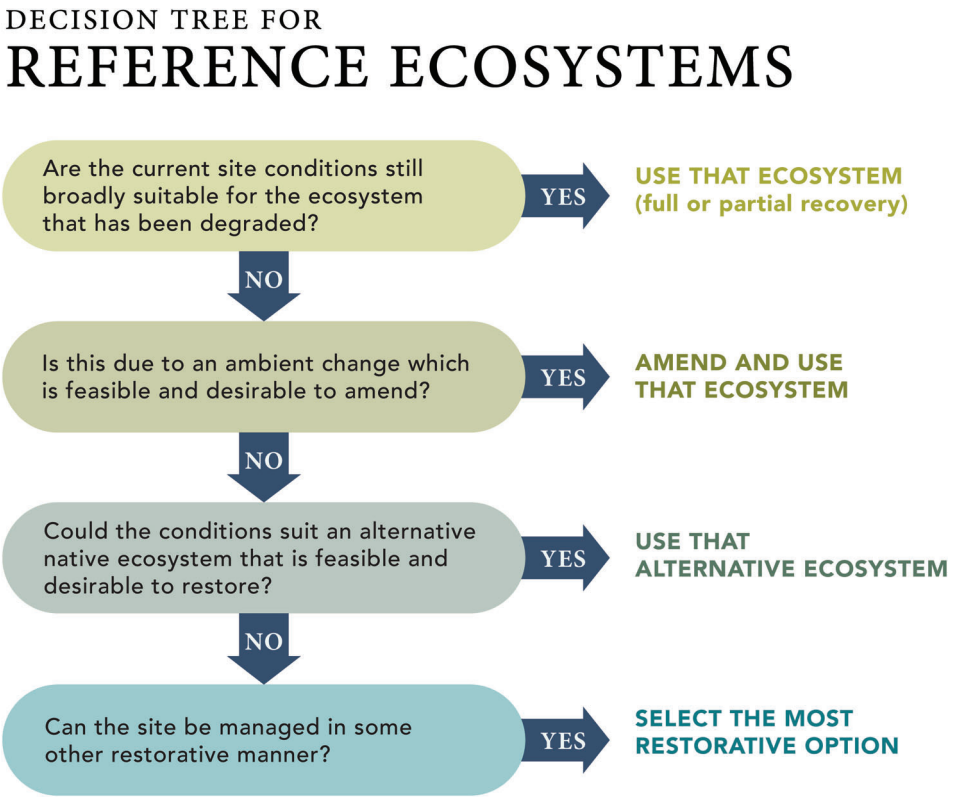

Figure 3. Decision tree to assist selection of appropriate native reference ecosystems for restoration projects.

Box 4. The importance of baselines.

In ecological restoration, the word baseline is used in two very different ways. In the Standards, baseline refers to the condition of a site at the beginning of the restoration process. In other contexts, baseline describes an ecosystem prior to degradation (e.g. as used by the Convention on Biological Diversity). The latter usage also applies to the concept of shifting (or declining) baselines that describe how some ecosystems may be more degraded than previously thought, or when current observers view ecosystems as nondegraded that previous observers would view as degraded. The idea of shifting baselines has been particularly well studied in marine ecosystems and fisheries. In the context of the Standards, the concept of shifting baselines must be considered when using reference sites to develop a reference model for ecological restoration, as a reference site may be perceived as nondegraded or minimally degraded, but may be missing important species or functions. Failure to consider that reference sites may be diminished could result in less accurate reference models.

In addition, this problem is important for mandatory restoration programs, as agencies may aim for lower standards based on erroneous ideas of what constitutes a nondegraded ecosystem. This may be of importance for biodiversity offset programs, which, if poorly designed, may contribute to continued degradation and loss of biodiversity. Furthermore, it has been demonstrated that even if full recovery of an ecosystem is possible, net losses of biodiversity and ecosystem functioning may continue over long time periods until full recovery can be attained. Consequently, ecological restoration programs, whether mandatory or voluntary, should strive to do more than seems necessary to secure overall net gains of biodiversity and ecosystem services.

areas, archeological sites, fenced military sites, or demilitarized zones) may indicate the trajectory of recovery of the ecosystem following a specified type of damage. Reference conditions may need to be inferred from the least-disturbed portions of the site, combined with successional models, historical data, and models of future change

Importantly, reference models should be based on the specific ecosystem attributes to be recovered, and account for both ecological complexity and temporal change (i.e. the successional or equilibrium dynamics of the ecosystem; see Section 4, Part 1 for discussion of these concepts). Six **key ecosystem attributes** (Table 2) can be used to describe the reference ecosystem. Together these six attributes contribute to overall ecosystem integrity, which arises from properties of diversity, complexity, and resilience inherent in functional native ecosystems. Given the large range of ecosystem types for which ecological restoration is needed, these attribute categories are broad rather than prescriptive.

Table 2. Description of the key ecosystem attributes used to characterize the reference ecosystem, as well as to evaluate 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.

Attribute	*Description*
Absence of threats	Direct threats to the ecosystem such as overutilization, contamination, or invasive species are absent
Physical conditions	Environmental conditions (including the physical and chemical conditions of soil and water, and topography) required to sustain the target ecosystem are present
Species composition	Native species characteristic of the appropriate reference ecosystem are present, whereas undesirable species are absent
Structural diversity	Appropriate diversity of key structural components, including demographic stages, trophic levels, vegetation strata and spatial habitat diversity are present
Ecosystem function	Appropriate levels of growth and productivity, nutrient cycling, decomposition, species interactions, and rates of disturbance
External exchanges	The ecosystem is appropriately integrated into its larger landscape or aquatic context through abiotic and biotic flows and exchanges

Reference models should not be used to immobilize an ecosystem at a specific point in time. An inherent property of ecosystems is that they change over time as a result of internal (e.g. changes in population growth rates) and external factors (e.g. physical disturbances). Reference models should be developed with an explicit focus on understanding temporal dynamics to develop feasible and relevant restoration designs that allow local species to recover, adapt, evolve, and reassemble.

Multiple reference models may be needed for a restoration project. First, large project sites or those with varied topography are likely to include a mosaic of ecosystems and their ecotones. Second, multiple or sequential references may be needed to reflect ecosystem dynamics or anticipated changes over time. Sites in successional ecosystems may be in the early phases of successional development immediately after treatment and later advance to other successional stages[2]. For ecosystems with complex equilibrium dynamics, multiple successional pathways may exist and multiple models may be necessary to attempt to describe different possible restoration outcomes. Such alternative states can result from changes in population densities or in environmental drivers or both in combination. Additionally, reference models may need adjustment over time based on results of project monitoring.

Traditional Cultural Ecosystems. Most ecosystems worldwide have been shaped by human utilization, to provide food, fiber, medicines, or culturally important artifacts (e.g. totems, spiritually significant tools). The **traditional cultural ecosystems** concept acknowledges that ecosystems are not just assemblages of organisms, but reflect co-evolution of plants, animals, and humans in response to past environmental conditions. The extent to which native ecosystems are the result of human modification is variable and often unclear; but it is well understood that extensive modifications have occurred and been maintained by traditional practices that are similar to natural disturbances. For example, the existence of grassy openings found within forests is often attributed to burning by Indigenous peoples. Where such human-utilized grassland ecosystems exhibit species and biophysical characteristics similar to those occurring in natural fire-maintained savannas and grasslands, such human-utilized areas should be considered native ecosystems. In these areas supporting native biodiversity, traditional management practices should be encouraged as a necessary part of ecosystem integrity. In fact, in some ecosystems, lack of traditional management (e.g. lack of traditional burning, grazing, harvesting, planting, seasonal flooding) drives degradation. Similarly, many of the ancient coppiced woodlands and unfertilized species-rich hay meadows of Europe, and other ancient, human-modified ecosystems in the Mediterranean region and the Sahel are examples of native ecosystems and appropriate reference models for ecological restoration. In the European Union legal context, these are referred to as **semi-natural ecosystems** (not cultural ecosystems), and include chalk grasslands, wet and dry heathlands, woodland pastures, seasonal mountain pastures, grazed salt marshes, Mediterranean shrublands and dehesas, and mesotrophic fish ponds.

Because of complex social–ecological histories in traditional cultural ecosystems, multiple complementary ecosystems may function as references for ecological restoration. In some cases, the restoration target may be an early successional stage of an ecosystem, which will be maintained through traditional management. Ancient or modern cultural ecosystems that are composed primarily of nonnative species, utilize artificial inputs (e.g. fertilizers), or are structurally or functionally distinct from regional native ecosystems (e.g. formal botanical gardens) are not appropriate reference models for ecological restoration as defined here.

Principle 4. Ecological Restoration Supports Ecosystem Recovery Processes

Ecological restoration actions are designed to assist natural processes of **recovery** that ultimately are carried out by the

[2]In contrast, ecosystems that do not exhibit successional phases will not require sequential references—e.g. the hyper-diverse Cape Floral Kingdom of southern Africa and the Southwest Australian biodiversity hotspots that contain old, stable, ecosystems developed on infertile substrates.

effects of time on physical processes and the responses and interactions of the biota throughout their life cycles. Restoration activities focus on reinstating components and conditions suitable for these processes to recommence and support recovery of ecosystem attributes, including capacity for self-organization and for **ecosystem resilience** to future stresses. These activities are planned and implemented based on the reference model (Principle 3), and agreed project targets, goals, and objectives (Principle 5).

The most reliable and cost-effective way to kick-start restoration is to harness the potential of remnant species (e.g. plants, animals, microorganisms) to regenerate (i.e. to colonize or expand from in situ components), but degraded ecosystems often require substantial intervention to compensate for lost **natural recovery potential** (see also Section 4, Part 2). An assessment is needed prior to planning appropriate treatments to determine the: (1) potential for regeneration after removal of the causes of degradation and (2) need to reinstate missing biotic and abiotic elements. This assessment should be informed by knowledge of the **functional traits** (particularly recovery mechanisms) of individual species likely to occur on or colonize the site, and predicted propagule flows and stores. Where knowledge gaps exist, tests of the recovery response in smaller areas is useful prior to application to larger ones. Restoration interventions focused in areas with high natural recovery potential could be prioritized to free resources later for areas requiring more intensive activities (see Section 4, Part 2).

Restoration can lead to unexpected results. Practitioners must be prepared to undertake additional treatments or engage in research to overcome barriers or limitations to natural recovery. Restoration actions designed to stimulate native species recovery, for example, may also stimulate a response from undesirable species present in the **propagule** bank, often requiring multiple follow-up interventions to achieve project goals.

Principle 5. Ecosystem Recovery Is Assessed against Clear Goals and Objectives, Using Measurable Indicators

In the planning phase of restoration projects, the project scope, vision, targets, goals, and objectives are identified, along with specific indicators to measure progress. Both ecological and social attributes of the project should be included (Box 5). Indicators can then be used to monitor progress over time, applying **adaptive management** approaches (Box 6). Adequate resources for monitoring must be allocated if effective monitoring is to take place.

Ecological targets, goals, and objectives will be strongly informed by a site assessment or baseline inventory. This assessment describes the state of the degraded site and informs both the identification of the reference model (Principle 3), and the degree of recovery required to approximate the reference condition. The baseline inventory describes current biotic and abiotic elements of the site, including its compositional, structural, and functional attributes, as well as external threats and subsidies. The inventory process is a key initial step to understand what is desirable and possible at a degraded site in terms of restoration targets, goals, objectives, and indicators. The inventory is used subsequently to detect changes over time relative to the baseline condition.

Assessments of progress toward the ecological target should include indicators for each of the six key ecosystem attributes of the reference ecosystem (Box 7). The project's ecological goals should address the degree of recovery sought for each attribute, with specific and measurable indicators to assess the site condition prior to project initiation. The same indicators are also monitored after project implementation to evaluate whether restoration actions are meeting the project's ecological

Box 5. Hierarchy of terms commonly used in project planning*

- The *Scope* is the broad geographic or thematic focus of a project.
- The *Vision* is a general summary of the desired condition one is trying to achieve through the work of the project. A good vision is relatively general, visionary (inspiring), and brief.
- The *Targets* identify the native ecosystems to be restored at a site as informed by the reference model, along with any social outcomes or constraints expected of the project.
- *Goals* are formal statements of the medium to long-term desired ecological or social *condition*, including the level of recovery sought. Goals must be clearly *linked to targets, measurable, time-limited*, and *specific*.
- *Objectives* are formal statements of the interim outcomes along the trajectory of recovery. Objectives must be clearly linked to targets and goals, and be *measurable, time-limited*, and *specific*.
- *Indicators* are specific, quantifiable measures of attributes that directly connect longer-term goals and shorter-term objectives. Ecological indicators are variables that are measured to assess changes in the physical (e.g. turbidity units), chemical (e.g. nutrient concentration), or biotic (e.g. species abundance) ecosystem attributes as guided by the reference model. Social–ecological or cultural indicators measure changes in human wellbeing such as participation in traditional practices, governance, language and education.

*Terms used here, with some adaptations, are based on those of the Open Standards for the Practice of Conservation (Conservation Measures Partnership 2013).

Box 6. Monitoring and adaptive management.

Monitoring restoration projects is essential to each of the following goals:
Generating social learning. Participatory monitoring engages stakeholders in the collection and analysis of data gathered from restoration activities. This partnership approach can lead to improved collaborative decision-making and strengthen stakeholder capacity and empowerment. Successful participatory monitoring addresses the questions and needs of stakeholders in a timely way. Methods are agreed upon collectively, are easy-to-use, and encourage social learning while building learning networks. As such, participatory monitoring is often more beneficial when it draws from information sources and methods of assessing reliability that are relevant for the stakeholders, rather than conventional scientific approaches.
Answering specific questions. Monitoring can be used to answer specific questions that improve understanding of ecological restoration and inform restoration decisions. Both require appropriately collected data and an effective experimental design that addresses the monitoring questions being asked. For instance, to determine the extent that project areas are recovering, best practice is to compare the restoration site to the reference model developed from pre-selected reference sites or information. This design, however, will not provide information on whether or not the treatments are responsible for causing the effect. To determine the extent that restoration interventions are having an effect, data must be collected before and after treatment on both control and treated sites (Before-After-Control-Impact or BACI experimental design). Such formal monitoring can resolve issues about new treatments or the return of organisms or processes when data are collected under an appropriate experimental design. Rigorous recording of specific restoration treatments and other conditions that might affect the results is also needed. Standard practice in such situations is for the initiator of the research to develop partnerships among scientists, practitioners, and the local community, to ensure that the project receives an appropriate level of scientific and practical advice and assistance to optimize its success and relevance.
Applying adaptive management. This form of "learning by doing" is a systematic approach for improving the practice of restoration. Adaptive management is not "trial and error." Properly applied, adaptive management improves our understanding of restoration by: (1) allowing stakeholders to explore alternative ways to meet restoration objectives; (2) predicting the outcomes of alternatives based on the current state of knowledge; (3) implementing one or more of these alternatives; (4) monitoring to learn about the impacts of restorative actions; and then (5) using the results to update knowledge and adjust restoration practices. Adaptive management can and should be the standard approach for any ecological restoration project, irrespective of how well-resourced that project may be. Fully implementing an adaptive management approach requires timely monitoring and evaluation of results, as well as funding for ongoing restoration.
A basic process necessary to identify whether restoration actions are working or need to be modified is to inspect the site routinely, and record observations of species responses (e.g. growth rates, flowering, regeneration, and absence or presence of weeds, pests, and disease). Formal sampling can involve a range of soil, water, vegetation, and animal sampling techniques. Design of monitoring schemes should occur at the planning stage of the project to ensure that the project's goals, objectives and their selected indicators are measurable, that the monitoring layout and scheduling aligns well, and that there are clear triggers for action if objectives are not met. If desired and appropriate, formal experiments can be designed, observing the conventions of sample size, replication, and the use of untreated controls to interpret results.
Providing evidence to stakeholders. Time-series photography provides visual evidence to stakeholders and regulators that goals are being met (i.e. securing images of the site from the same photo point locations, prior to and following treatment to show changes over time). At small sites, fixed photo-points can be established on the ground, whereas for larger sites, remote-sensing imagery may be more efficient. Because such imagery only provides visualization of changes occurring, well-funded projects (particularly those under regulatory controls) are usually expected to undertake formal quantitative monitoring. This is based on a monitoring plan that identifies, among other things, monitoring questions, sampling design, timeframes, specific data collection instructions, who is responsible, the planned analysis, and frameworks for response and communication to regulators, funding bodies, or other stakeholders.

goals and objectives. To evaluate progress, each restoration objective must clearly articulate: (1) the indicators that will be measured (e.g. percentage canopy cover of native 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). For projects where full recovery may be possible and is desirable, the ecological target will align with the reference model. When only partial recovery is anticipated, however, the target and reference model will not fully align. For example, the target ecosystem may lack some species or include nonnative surrogates or invaders, or the ecological targets may be modified to meet social targets.

Social goals vary widely among projects and arise from a variety of social considerations (see Principle 1). After meaningful consultation with stakeholders, social goals should be identified in the project plan including descriptions of the rationale for any trade-offs between ecological and social costs and benefits. Project reports can then recognize and highlight the benefits to society and to ecosystems that may flow from the project.

Box 7. Hypothetical planning example including integrated ecological and social goals.

Scope: Two 5-ha Garry oak woodlands connected by an open meadow and a lake in the Southern Gulf Islands, British Columbia, Canada.
Current condition: Grazing and fragmentation have resulted in a decline in the diversity of woodland birds and altered vegetative composition in two Garry oak woodland remnants. These two woodlands, connected by an overgrazed meadow, contain 30% native and 50% nonnative cover of herbaceous and woody plant species. The remaining 20% cover is bare ground. The lake has a high *Escherichia coli* count from leachates from grazed soils. Floating water plants increase following rain events, which lead to occasional fish kills.
Vision: The return of healthy ecosystems cared for and enjoyed by the residents of the islands, resulting in renewed social cohesion and opportunities for sustainable ecosystem management.
Ecological Targets: Restored Garry oak woodlands (wooded) and meadows (semi-open) with mature oak trees underlain with carpets of spring wildflowers. The local Indigenous community keeps the meadows clear of underbrush, to cultivate camas. The bulbs of this blue wildflower provide an important source of food. The open water lake is the habitat for rainbow trout, smallmouth bass and pumpkin-seed sunfish. A wetland serves as a transition from the lake to the shore. River otters swim among the yellow pond lilies, and red-winged blackbirds balance on cattails.

Goals (ecological and social):

(1) Reduced active sedimentation and *E. coli* count in waterways to within health department standards for swimming within 5 years;
(2) Reduced eutrophication, with the adult lake trout population exceeding 20 catches per unit effort within 5 years;
(3) Neighbors comprise 80% of volunteers in a stewardship program within 5 years;
(4) Two bird species, absent for 10 years, prior to the beginning of the project, return to breed at the site within 10 years;
(5) Renewed social cohesion within the community, as evidenced by 50% improvement of place compared to baseline levels within 10 years;
(6) Garry oak woodland with >90% of the native plant species of the reference model within 15 years; and,
(7) Herbaceous matrix between the remnants recovered with 80% of the native plant species characteristic of the reference model for Garry oak meadow within 15 years.

Objectives (ecological and social) as measured by specific indicators:

(1) Cessation of livestock grazing within 1 year;
(2) Abundance of nonnative plants reduced to <25% cover within 2 years;
(3) At least 25 volunteers join a stewardship program with neighbors comprising >50% of the membership within 2 years;
(4) Rates of recruitment of two or more native woody species increase by 10% within 5 years in both woodland remnants;
(5) Native woody plant density increases to at least 100 stems/ha of trees and 100 stems/ha of shrubs within 3 years;
(6) Native species richness within the meadow increases to at least 6 grass and 10 forb species/10 m^2 within 5 years; and
(7) Field visits by local school children increases by 50% within 5 years.

*Note that these numbers are all hypothetical examples and not a guide.

Principle 6. Ecological Restoration Seeks the Highest Level of Recovery Attainable

An ecological restoration project adopts the goal of achieving the highest level of recovery possible, relative to the six attributes of the reference ecosystem. Recovery, whether full or partial, takes time and may be slow. Thus, managers should adopt a policy of continuous improvement informed by sound monitoring. Such a policy can allow managers to continually upgrade and build on project goals to advance initial recovery toward progressively higher outcomes. One approach for designing projects and tracking progress over time is use of the Five-Star System and Ecological Recovery Wheel.

Five-Star System and Ecological Recovery Wheel. The Five-star System (Tables 3 & 4) and the Ecological Recovery Wheel (Fig. 4) are provided as tools to help managers, practitioners, and regulatory authorities establish, visualize, and communicate the level of recovery aspired to and to progressively evaluate and track the degree of native ecosystem recovery over time relative to the reference model. These tools also provide a means to report changes from the **baseline condition** relative to the reference.

Importantly, the Five-star System focuses on ecological measurements, rather than social ones; it is not intended as a tool to evaluate the progress of a restoration project against its social goals (see Principle 1). Rather, managers are encouraged to use

the Five-star System and Ecological Recovery Wheel to illustrate their project's ecological targets and goals relative to the six key attributes and to provide a monitoring framework. The idea is to aim high and show progress over time, even if full recovery is not initially possible or something less than full recovery is the goal.

Notes for Interpreting the Five-star System. A number of responses are provided to frequently asked questions:

- Since being described in McDonald et al. (2016*a*), the Five-star System and companion Ecological Recovery Wheel have been increasingly adapted and utilized by practitioners and scientists in a wide variety of ecosystems around the world (e.g. rivers in the United Kingdom, coral reefs in Mexico, forests and woodlands in Australia).
- Evaluation using the Five-star System must be site- and scale-specific. The Five-star System was developed for implementation at the site level, but can be applied at the program level by separately evaluating sites using the Five-star System and then aggregating data from multiple sites to display degree of recovery (average, minimum, maximum) for larger programs.
- Indicators described in Tables 3 and 4 are generic and should be interpreted more specifically by managers to suit their specific ecosystem or project, whether terrestrial or aquatic.
- The Five-star System can be used as a framework for interpreting either quantitative or qualitative monitoring. The stars can be readily quantified using many monitoring systems and statistical approaches, e.g. using response ratios (ratio of the mean value of a variable at the restoration site compared to that of the reference model), which are commonly employed by scientists and practitioners to measure restoration outcomes. Regardless of whether qualitative or quantitative approaches are used, it is imperative to explicitly specify the level of detail and degree of formality of the monitoring from which conclusions are drawn. This means that the Ecological Recovery Wheel or an evaluation table should not be used as evidence of restoration progress without also citing the monitoring data on which it is based.
- Each restoration project attribute does not necessarily start at a zero or one-star ranking. This is because the ranking is with respect to similarity to (or differences from) the reference model, with respect to a set of measurable indicators relevant to the sub-attributes. Sites including remnant biota and unaltered substrates will start at higher rankings, whereas sites with impaired substrates or missing biota will start at lower rankings. Whatever the entry point of a project, the aim will be to assist the ecosystem to progress along the trajectory of recovery insofar as possible. A zero-star score would be noted in written reports or as a zero in spreadsheets and represented by an empty cell in the Ecological Recovery Wheel.
- By adding additional colors or patterns, or creating sequential Recovery Wheels, the user can show the baseline condition, proposed end condition, and conditions at multiple points during the recovery process.
- The Five-star System is not meant to evaluate the individual performance of practitioners or the value of projects. Some projects, because of site constraints, cannot aspire to five stars.

Principle 7. Ecological Restoration Gains Cumulative Value when Applied at Large Scales

Every ecological restoration project can have beneficial outcomes regardless of size, including increasing numbers and population sizes of depleted species, reducing populations of invasive species and other threats, and improving ecosystem functions such as nutrient cycling. However, many ecological processes function at landscape, watershed, and regional

Table 3. Summary of generic standards for one to five star recovery levels. Each level is cumulative. The different attributes may have different rankings due to varying rates of response to treatments as well as project goals. More detailed generic standards for the six key ecosystem attributes are given in Table 6. This system is applicable to any level of recovery where a reference ecosystem is used.

Number of stars	*Summary of recovery outcome*
★	Ongoing deterioration prevented. Substrates remediated (physically and chemically). Some level of native biota present; future recruitment niches not negated by biotic or abiotic characteristics. Future improvements for all attributes planned and future site management secured
★★	Threats from adjacent areas starting to be managed or mitigated. Site has a small subset of characteristic native species and low threat from undesirable species onsite. Improved connectivity arranged with adjacent property holders
★★★	Adjacent threats being managed or mitigated and very low threat from undesirable species onsite. A moderate subset of characteristic native species is established and there is some evidence of ecosystem function commencing. Improved connectivity at the landscape scale is in evidence
★★★★	A substantial subset of characteristic biota present (representing all species groupings), providing evidence of developing community structure and of ecosystem processes. Improved connectivity established and surrounding threats being managed or mitigated
★★★★★	Establishment of a characteristic assemblage of biota to a point where structural and trophic complexity to a level of very high similarity to the reference ecosystem is likely to develop with minimal further restoration interventions. Appropriate cross-boundary flows are enabled and commencing and resilience is restored with return of appropriate disturbance regimes. Long-term management arrangements in place

Table 4. Sample one to five star recovery scale interpreted in the context of 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. As a generic framework, users must develop indicators and monitoring metrics specific to the ecosystem and sub-attributes they identify.

Attribute	★	★★	★★★	★★★★	★★★★★
Absence of threats	Further deterioration discontinued, and site has tenure and management secured	Threats from adjacent areas beginning to be managed or mitigated	All adjacent threats managed or mitigated to a low extent	All adjacent threats managed or mitigated to an intermediate extent	All threats managed or mitigated to high extent
Physical conditions	Gross physical and chemical problems remediated (e.g. excess nitrogen, altered pH, high salinity, contamination or other damage to soil or water)	Substrate chemical and physical properties on track to stabilize within range of reference ecosystem	Substrate stabilized within range of reference ecosystem and supporting growth of characteristic native biota	Substrate securely maintaining conditions suitable for ongoing growth and recruitment of characteristic native biota	Substrate exhibiting physical and chemical characteristics highly similar to that of the reference ecosystem with evidence they can indefinitely sustain species and processes
Species composition	Some colonizing native species present (e.g. ~2% of species in the reference ecosystem). Moderate onsite threat from nonnative invasive or undesirable species. Regeneration niches available	A small subset of characteristic native species establishing (e.g. ~10% of reference). Low to moderate onsite threat from nonnative invasive or undesirable species	A subset of key native species (e.g. ~25% of reference) establishing over substantial proportions of the site. Very low onsite threat from nonnative invasive or undesirable species	Substantial diversity of characteristic native biota (e.g. ~60% of reference) present across the site and representing a wide diversity of species groups. Very low onsite threat from nonnative invasive or undesirable species	High diversity of characteristic native species present (e.g. >80% of reference), with high similarity to the reference ecosystem; improved potential for colonization of more native species over time. No known onsite threat from undesirable species
Structural diversity	One or fewer biological strata present and no spatial patterning or community trophic complexity relative to reference ecosystem	More strata present but low spatial patterning and trophic complexity, relative to reference ecosystem	Most strata present and some spatial patterning and trophic complexity relative to reference site	All strata present. Spatial patterning evident and substantial trophic complexity developing relative to the reference ecosystem	All strata present and spatial patterning and trophic complexity high. Further complexity and spatial patterning able to self-organize to highly resemble reference ecosystem
Ecosystem function	Substrates and hydrology are at a foundational stage only, capable of future development of functions similar to the reference	Substrates and hydrology show increased potential for a wider range of functions including nutrient cycling, and provision of habitats and resources for other species	Evidence of functions commencing (e.g. nutrient cycling, water filtration, and provision of habitat and resources for a range of species)	Substantial evidence of key functions and processes commencing including reproduction, dispersal, and recruitment of native species	Considerable evidence of functions and processes on a secure trajectory toward that of the reference and evidence of ecosystem resilience, tested by reinstatement of appropriate disturbance regimes
External exchanges	Potential for exchanges (e.g. of species, genes, water, fire) with surrounding landscape or aquatic environment identified	Connectivity for enhanced positive (and minimized negative) exchanges arranged through cooperation with stakeholders. Linkages being reinstated	Positive exchanges between site and external environment becoming evident (e.g. more species, gene flows, etc.)	High level of positive exchanges with other native ecosystems established; control of undesirable species and disturbances	Evidence that external exchanges are highly similar to reference, and long-term integrated management arrangements with broader landscape in place and operative

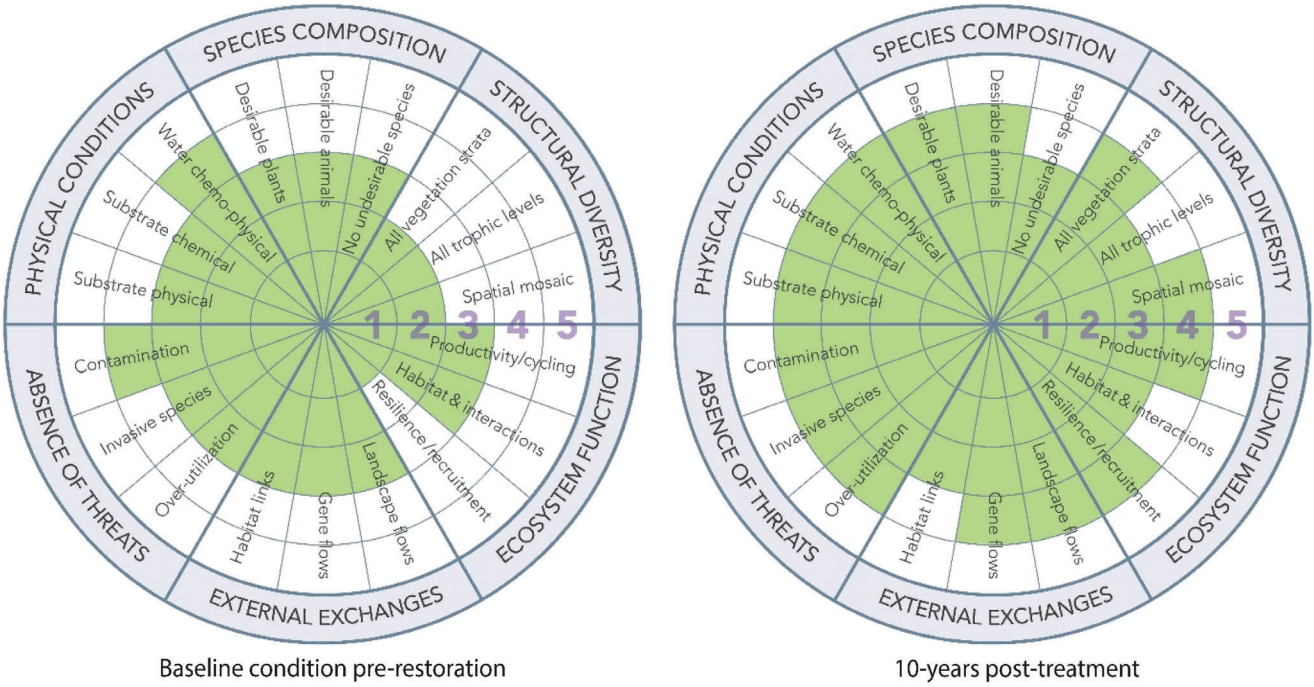

Figure 4. The ecological recovery wheel is a tool for conveying progress of recovery of ecosystem attributes compared to those of a reference model. In this example, the first wheel represents the condition of each attribute assessed during the baseline inventory stage of the project. The second wheel depicts a 10-year-old restoration project, where over half its attributes have attained a four-star condition. Practitioners familiar with the project goals, objectives, site-specific indicators, and recovery levels achieved to date can shade the segments for each sub-attribute after formal or informal evaluation. Blank templates for the diagram and its accompanying form are in Appendix 2. Sub-attribute labels can be added or modified to best represent a particular project. For symmetry of design, three sub-attributes are used in this example, but there may be more, or fewer, needed depending on the project.

scales (e.g. gene flow, colonization, predation, ecological disturbances). Degradation occurring at larger scales can overwhelm smaller restoration efforts. For example, species with large minimum habitat requirements or that require greater trophic complexity may not be accommodated in small projects. To counter climate change, substantially increasing the rate of **carbon sequestration** by greater production of plant and animal biomass (including biomass in soils) is urgently needed. Likewise, water security (in terms of quality, quantity and flows) is most effectively achieved by working at the landscape scale and linking terrestrial and aquatic systems. Thus, some ecological restoration projects must be conducted at large scales (e.g. hundreds or thousands of hectares) to provide desired environmental and ecological benefits. Additionally, planning and prioritizing site-level activities are necessary as part of integrated landscape planning efforts (see Section 4, Part 3). Landscape-scale planning can help avoid situations in which productive uses of an ecological restoration site (e.g. agriculture or forestry) are simply relocated to other areas causing additional degradation. Planning ecological restoration at larger scales must ensure that ecological restoration efforts result in net-positive landscape change.

Challenges and Potential Solutions. Increasing the scope of ecological restoration can bring some economies of scale, but can also increase the risk of over-extending financial, institutional, and infrastructural resources, particularly where ecosystem responses to treatments are unpredictable. Social challenges include identifying all relevant stakeholders and their specific needs and interests, and achieving agreement among stakeholders with competing interests, especially where political institutions are weak, or where strong economic and power inequalities exist among landowners. A mechanism such as participatory land use planning needs to be in place for dealing with such disagreements. For scale-sensitive and time-sensitive issues, treatments are usually tested at a small scale prior to broader application. In some cases, investing in gradual improvements at larger scales (e.g. to control threats such as invasive species or non-point pollution), may achieve greater results than more intense work at smaller scales or over shorter periods of time. Increased scale of a restoration project confers an advantage, however, only where it represents an increase in the scale at which benefits (e.g. increased abundance of native species, decreased pest species abundance, or increased carbon sequestration) are improved. For this reason, and to avoid undervaluing smaller projects that may be of high ecological importance (e.g. the restoration of small fens), scale should be evaluated only as a multiplier of the other values achieved. A range of potential co-benefits should be considered when predicting whether a project is likely to make a difference at larger scales (Table 5). Furthermore, larger-scale functions can be enhanced

Table 5. Project characteristics that contribute to a project's potential to improve ecosystem recovery, particularly at scale. For optimal success, the project must be based on sound ecological information and be well embedded in local cultures and institutions.

Characteristic	*Examples*
Strategic location and timeliness	Restoration projects deploy strategies that make the most of scarce resources and known leverage points for effective restoration. Projects are prioritized in terms of: (1) goals with greater urgency or that accelerate the achievement of other goals; and (2) areas with greater recovery potential.
Extinction risk reduction	Projects have added value when they help recover threatened populations, species, or ecosystems. This work is guided by formal listings in place in many countries, usually linked to or consistent with International Union for Conservation of Nature (IUCN) Red Lists.
Threat pervasiveness	Projects addressing large-scale or pervasive threats can influence areas well beyond the project site. For example, projects that achieve substantial carbon sequestration, reduce contamination into waterways, or control pest plants or animals, improve outcomes locally and contribute to improved outcomes elsewhere.
Security of institutional support	Large-scale projects need long-term security to ensure that benefits resulting from resources invested will persist over time. Formal protection of the site through legal tenure arrangements is ideal, as is ensuring that long-term political and economic commitments are made by the site's major public and private stakeholder institutions at local, regional, or national scales.

via increased beneficial connectivity (e.g. wildlife corridors), including linkages to adjacent sites undergoing restorative interventions (Principle 8; Section 4, Part 3). It is important to note that cumulative value may only be achieved in the long term, meaning that those initially investing in restoration may not directly benefit.

One mechanism to scale-up ecological restoration is to ensure that projects are strategically integrated within larger **restoration programs** that contain multiple projects involving not only restoration, but also other restorative activities carried out in different landscape units, with varying partners changing over time. These may consist of many restoration project sites that are functionally and physically linked. A large-scale ecological restoration program is typically coordinated by a coalition of government agencies, nonprofits, botanical gardens, and other allies, and involves large, complex planning processes. Examples include the Comprehensive Everglades Restoration Plan (CERP) in the USA, and the Atlantic Forest Restoration Pact in Brazil, both coalitions of governmental agencies, private sector, NGOs, and research institutions. Very large restoration sites and projects may create challenges for selecting targets and for developing reference models due to lack of comparable reference sites (see Section 4, Part 1) or to their complexity, although new tools such as LiDAR may help overcome the latter challenges in some landscapes.

Principle 8. Ecological Restoration Is Part of a Continuum of Restorative Activities

As ecosystem degradation continues globally, many countries and communities are adopting policies and measures designed to conserve biodiversity, recover ecological integrity and resilience, improve the quality and quantity of ecosystem services, and transform the way societies interact with nature. Ecological restoration is one of a range or family of **restorative activities** that can be conceived of as a continuum, wherein the degree of distinction between one type of activity to another is quite minimal, but from the most basic action to the most advanced, the distinction is quite significant. A restorative activity is one that directly or indirectly supports or attains the recovery of ecosystem attributes that have been lost or degraded. Conceptually, the **restorative continuum** (e.g. as depicted in Fig. 5) offers a holistic approach to repairing the world's ecosystems, enabling practitioners to apply the most appropriate and effective treatment given the ecological, social, and financial conditions (both opportunities and constraints). The restorative continuum provides a context for understanding how different activities relate to each other, while also helping identify practices best suited to a particular context. The continuum includes four major categories of restorative practices: (1) reduced societal impacts (i.e. in actions that reduce impacts through less damaging ways to consume and utilize ecosystem services across all sectors (Box 8)); (2) **remediation** (i.e. of polluted and contaminated sites); (3) **rehabilitation** (i.e. of areas including those used for production or human settlement; Box 9); and (4) **ecological restoration**. Reduced societal impacts, remediation, and rehabilitation practices are restorative to the extent that they reduce causes and ongoing effects of degradation, enhance potential for ecosystem recovery, and promote a transition to sustainability. As such they are also considered **allied activities** to ecological restoration. Some projects or programs may cover more than one category, particularly those carried out within larger frameworks, such as nature-based solutions (including **green infrastructure**), and **Forest Landscape Restoration** (FLR). These frameworks often incorporate one or more allied activities alongside ecological restoration. To be considered restorative, project or landscape level efforts must result in a net-positive effect on environmental conditions. For example, activities that do not or will not improve current environmental conditions or those that cause harm (e.g. **afforestation** of native grasslands causing a net loss for biodiversity) do not qualify as restorative.

Ecological restoration and allied activities can be viewed as an integrated whole within a broad sustainability paradigm (see Section 4, Part 3), rather than as disconnected or competing activities. Restorative activities are cumulatively beneficial,

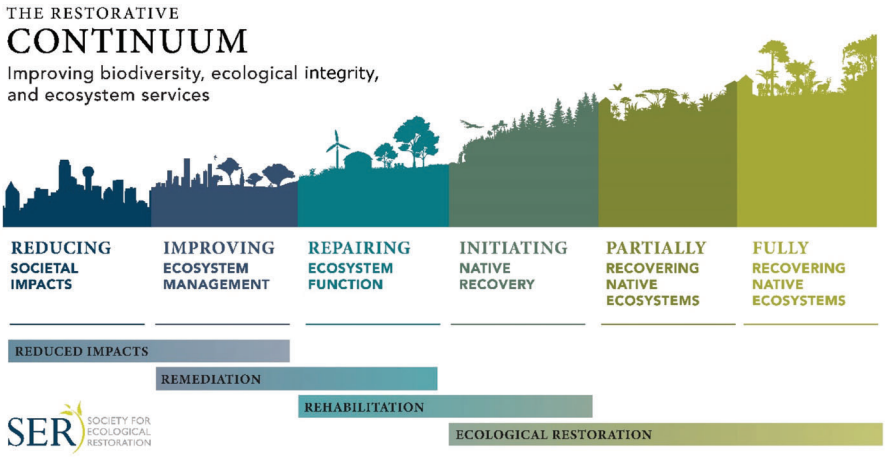

Figure 5. The restorative continuum includes a range of activities and interventions that can improve environmental conditions and reverse ecosystem degradation and landscape fragmentation. The continuum highlights interconnections among these different activities, and recognizes that the specific characteristics of the locality slated for restorative actions dictates the activities best suited for different landscape units. As one moves from left to right on the continuum, both ecological health and biodiversity outcomes, and quality and quantity of ecosystem services increase. Note that ecological restoration can occur in urban, agricultural, and industrial landscapes.

Box 8. Reduced impacts.

In the context of global environmental degradation, there is an urgent need to find ways to reduce adverse environmental impacts that flow from the way societies extract, produce, market, consume, and dispose of ecosystem goods. On the production side, increasing regulation in many regions of the world is resulting in more ecologically informed farming, forestry, fisheries, and mining methodologies. These activities have potential to reduce negative impacts of pollution and contamination, fragmentation of intact ecosystems, further clearing of native ecosystems, overharvesting, and the spread of invasive species. On the consumption side, a combination of regulation and increasing social expectation is changing some manufacturing practices and social behaviors, particularly in urban areas where more than half of the world's population now consumes goods and services at increasing rates per capita. While solutions can be evasive and greenwashing common, activities that genuinely aim to mitigate or attain a net reduction in human impacts (and thus improve potential for ecosystem recovery) can be considered allied to ecological restoration and clearly part of the restorative continuum.

Box 9. Rehabilitation.

Rehabilitation is a generic term used for ecological repair activities that aim to restore ecosystem functioning rather than the biodiversity and integrity of a designated native reference ecosystem. Rehabilitation activities are well suited to a broad range of land and water management sectors where substantial native ecosystem recovery is not possible or desirable due to competing and legitimate human needs. When rehabilitation is used for mined lands or post-industrial sites, it is sometimes called reclamation. The progress of ecological recovery for many rehabilitation projects can be tracked using the Five-star System and Ecological Recovery Wheel, where improvements in one or more ecosystem attributes can be demonstrated. To use the recovery wheel for demonstrating progress toward rehabilitation, the outer perimeter of the wheel would be desired values of the key ecosystem attributes, rather than values of these attributes from the native ecosystem reference model. Under the concept of "continuous improvement" (see Principle 6), rehabilitation projects achieving some improvements in ecological conditions can later be targeted for ecological restoration. For instance, where revegetation of a degraded rangeland, or post-mine site, with a mix of native and nonnative plant species and native microsymbionts has resulted in improved soil function, restoration plans can be developed that include harvesting nonnative species and replacing them with native species as well as taking other actions to assist the system to recovering to the condition it would have been in if degradation had not occurred. In some cases where soil has been stabilized with nonnative species, native species can be added (or helped to recover spontaneously) and nonnative species removed to ultimately assist the recovery of a native ecosystem.

improving outcomes from one level to the next. The conceptual frameworks and best practices of ecological restoration conveyed in these Standards can inspire and inform many actions that can be deployed to improve the overall health and resilience of the environment.

Conceptualizing management actions by means of this continuum (along with having an understanding of ecological restoration principles and standards) should assist governments, industries, and communities in achieving integrated "net gain" improvements in condition that will accelerate positive change at larger scales (Principle 7). Recommendations of performance measures for restorative activities across a range of industry, government, and community sectors or contexts are in Table 6. Regardless of the sector or context, it is beneficial to adopt practices of continuous improvement, and prioritize implementation of ecological restoration as the restorative activity of choice, wherever feasible. Where ecological restoration is inappropriate or not viable (e.g. where remediation or reducing societal impacts may be the only option), restorative work should aim for the highest possible recovery level. As with ecological restoration, small and ongoing improvements can be cumulative at larger scales for allied activities.

Section 3 — Standards of Practice for Planning and Implementing Ecological Restoration Projects

The following lists specific standard practices used in: (1) planning and design; (2) implementation; (3) monitoring and evaluation; and (4) maintaining ecological restoration projects after completion, particularly where professional staff or contractors are engaged. These Standards of Practice fully incorporate SER's Code of Ethics (SER 2013). They are adaptable to the size, complexity, degree of degradation, regulatory status, and budget of any project, but not all steps will be possible for all projects. The steps described in the standards are not always sequential. For instance, the standards include monitoring after implementation, because the bulk of the monitoring effort may occur post-treatment; however, activities critical to monitoring must begin before project initiation, because of the need to design monitoring plans, develop budgets and secure funding, and collect pre-treatment data prior to implementation of restoration treatments.

1 **Planning and design**

1.1 Stakeholder engagement. Meaningful, informed, reciprocal engagement is undertaken preferably at the initial planning stage of a restoration project with all key stakeholders (including the land or water owners or managers, industry interests, neighbors, and local community and Indigenous stakeholders) and continues throughout the duration of a project. Engagement ideally includes training local people to provide committed, long-term monitoring and collaborative knowledge generation and dissemination. Key steps are to:

1.1.1 Include a schedule for stakeholder engagement throughout project lifespan. Where possible, participatory planning and restoration plan co-design are implemented, and local community capacity building and training are included (See tool: The Open Standards for the Practice of Conservation).

1.1.2 Perform due diligence to ensure that stakeholder rights, including land tenure, are understood and respected throughout the restoration process.

1.2 Context assessment. Plans and stakeholder engagement are informed by local and regional conservation and sustainability goals and priorities, and spatial planning and:

1.2.1 Include diagrams or maps of the project in relation to its surrounding landscape or aquatic environment;

1.2.2 Identify ways to improve beneficial connectivity between habitats at the restoration site, and increase beneficial external ecological exchanges with other native ecosystems to improve landscape-level flows and processes, including colonization and gene flow between sites; and,

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

1.3 Assessment of security of site tenure and scheduling of post-treatment maintenance. Evidence of potential for long-term conservation management of the site is required before investing in restoration. Restoration plans should thus:

1.3.1 Identify site-tenure security to enable long-term restoration and allow appropriate ongoing access for monitoring and management; and,

1.3.2 Identify plan for site maintenance after project completion to ensure that the site does not regress into a degraded state.

1.4 Baseline inventory. The baseline inventory documents 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 should:

1.4.1 Identify native, ruderal, and nonnative species persisting on the site, particularly threatened species or communities and invasive species;

1.4.2 Record status of current abiotic conditions (through photographs 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;

Table 6. Recommended performance measures for restorative activities across a range of industry, government, and community sectors or contexts. Note: The "star" score refers to the Five-star System described in principle 6. Unless otherwise specified, star scores in this table are assumed to be an average of all six attribute scores.

Sector or context	*Restorative activity and recommended performance standard*
Protected area management	• *Native ecosystems with potential for full recovery:* Ecological restoration to five-star level • *Native ecosystems with potential for only partial recovery:* Ecological restoration ideally to four-star, but a minimum three-star level • *Single species recovery programs or activities*: Highly valued components of larger programs that should aspire to the highest standards
Urban conservation areas and green space	• *Native ecosystems with potential for full recovery for some attributes*: Ecological restoration to five-star level wherever possible, or at least four-star level • *Native ecosystems or areas adjacent to native ecosystems with potential for only partial recovery*: Ecological restoration to the highest aspirational level practicable but the minimum of three-star level for biological attributes • *Converted parks and gardens*: Rehabilitation to a minimum two-star level for the ecosystem function attribute or at least sustainable utilization with no deleterious effect on native ecosystems and if possible, provision for additive ecological benefits to the native ecosystem
Forestry	• *Native forest restoration for biodiversity conservation:* Ecological restoration to a five-star level • *Native forestry:* Ecological restoration to a four- to five-star level (between logging cycles) • *Reforestation adjacent to native ecosystems:* Ecological restoration to the highest aspirational level practicable but at least a three-star level • *Reforestation primarily for ecosystem services:* Rehabilitation to a minimum two- to three-star level for the ecosystem function attribute, or at least sustainable utilization (between logging cycles) with no deleterious effect on native ecosystems, preferably with added ecological benefits
Fisheries	• *Native ecosystems with potential for full recovery:* Ecological restoration to a five-star level • *Native ecosystems with potential for only partial recovery:* Ecological restoration to the highest aspirational level practicable but a minimum of three-star level • *Activities adjacent to native ecosystems:* Rehabilitation to a minimum two-star level for the ecosystem function attribute, or at least sustainable utilization with no deleterious effect on adjacent native ecosystem, preferably with added ecological benefits
Utility corridors	• *Native ecosystems with potential for full recovery:* Ecological restoration to a five-star level • *Native ecosystems or areas adjacent to native ecosystems with potential for only partial recovery:* Ecological restoration to the highest aspirational level practicable but a minimum of a three-star level at least for the biological attributes • *Within utility corridors (not native ecosystems):* Rehabilitation to a minimum two-star level for the ecosystem function attribute, or at least sustainable utilization with no deleterious effect, preferably with added ecological benefits for native ecosystems
Agriculture and production horticulture	• *Native ecosystems with potential for full recovery*: Ecological restoration ideally to a five-star level • *Recovery of agricultural productivity/ecological agriculture adjacent to native ecosystems*: Ecological restoration to the highest aspirational level practicable but at least a three-star level • *Native ecosystems with potential for only partial recovery*: Ecological restoration to the highest aspirational level practicable but minimum of a two- to three-star level for at least the biological attributes • *Recovery of agricultural capacity for ecosystem services*: Rehabilitation to a minimum two-star level for the ecosystem function attribute or at least sustainable utilization with no deleterious effect on native ecosystems, preferably with added ecological benefits
Mining, quarrying, and oil and gas drilling sites	• When intact or near-intact native ecosystems are impacted (native ecosystems with potential for full recovery): Ecological restoration to a five-star level • When degraded native ecosystems are impacted (native ecosystems with potential for only partial recovery): Ecological restoration to the highest aspirational level practicable, that is three-star level or higher • Impacts on already converted (reallocated) landscape units with low potential for native recovery: Rehabilitation to one to two stars for the ecosystem function attribute or at least sustainable utilization with no deleterious effect on native ecosystems, preferably with added ecological benefits

1.4.3 Detect type and degree of drivers and threats that have caused degradation on the site and ways to eliminate, mitigate, or adapt to them (for a standard Threats Taxonomy, see the Open Standards Threats Classification). This includes assessment of:

- 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 diversity supplementation for species reduced to non-viable populations due to fragmentation (see Section 4, Part 3); and,
- Current and anticipated effects of climate change (e.g. temperature, rainfall, sea level, marine acidity) on species and genotypes with respect to likely future viability.

1.4.4 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 present, priority recovery areas and any distinct spatial areas requiring different treatments;

1.5 Native reference ecosystem(s) and reference models. Plans identify target native reference ecosystems and an appropriate reference model (Principle 3; Section 4 Part 1) based on multiple indicators of the six key ecosystem attributes (Table 2; Fig. 4) at a suitable number of reference sites. In some cases, descriptions of intact ecosystems may be available from previous assessments or models or environmental agency guidelines. Specifically, plans:

1.5.1 Document substrate characteristics (biotic or abiotic, aquatic or terrestrial);

1.5.2 List major characteristic species (representing all plant-growth forms and functional groups of micro- and macrofauna, including pioneer and threatened species);

1.5.3 Identify the ecosystem's functional attributes, including nutrient cycles, characteristic disturbance and flow regimes, successional pathways, plant–animal interactions, ecosystem exchanges, and any disturbance-dependence of component species;

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

1.5.5 In cases where extant ecosystems are being disturbed and then restored, preexisting intact ecosystems must be mapped in detail prior to site disturbance;

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

1.6 Vision, targets, goals and objectives. Clear and measurable goals and objectives are needed to identify the most appropriate actions, ensure that all project participants have a common understanding of the project, and measure progress (see Monitoring below). Plans must clearly state:

1.6.1 Project vision and ecological and social targets, including a description of the site and the native ecosystem to be restored;

1.6.2 Ecological and social goals including level of ecological recovery sought (i.e. condition or state 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 should quantify, where possible, degree of the reference ecosystem attributes to be attained. The social goals must be explicit and realistic, considering the time frame and social capital available in the area.

1.6.3 Objectives are the changes and immediate outcomes needed to achieve the target and goals relative to any distinct spatial areas within the site. Objectives are stated in terms of measurable and quantifiable indicators to identify whether or not the project is reaching its objectives within identified time frames. In addition to indicators, objectives should include specific actions, quantities, and time frames.

1.7 Restoration treatment prescriptions. Plans contain clearly stated treatment prescriptions for each distinct restoration area, describing what, where, and by whom treatments will be undertaken, and their order or priority. Where knowledge or experience is lacking, adaptive management or targeted research that informs appropriate prescriptions will be necessary. If there is uncertainty, the Precautionary Principle should be applied in a manner that reduces environmental risk.

Plans should:

1.7.1 Describe actions to be undertaken to eliminate and mitigate, or adapt to causal problems; and,

1.7.2 Identify and justify specific restoration approaches, descriptions of specific treatments

for each restoration area, 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 them amenable to the recovery of target biota and ecosystem structure and functions;
- Effective and ecologically appropriate strategies and techniques to control undesirable species to protect desirable species, their habitats, and the site;
- Ecologically appropriate methods to facilitate regeneration or achieve reintroduction of any missing species;
- 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); and,
- Appropriate species selection, genetic sourcing, and procurement of biota to be reintroduced (see Appendix 1).

1.8 Analyzing logistics. Analysis of potential for resourcing the project and of likely risks is required before undertaking a restoration plan. To address practical constraints and opportunities including plans:

1.8.1 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;

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

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

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

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

1.9 Establishing process for project review. Plans include a schedule and time frame to:

1.9.1 Carry out stakeholder and independent peer review as required; and,

1.9.2 Implement plan review in light of new knowledge, changing environmental conditions, and lessons learned.

2. **Implementation**

The implementation phase may be short or long, depending on the project and circumstances. During the implementation phase, restoration projects are managed to:

2.1 Protect the site from damage. 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, trampling), chemical contamination (e.g. over-fertilizing, pesticide spills) or biological contamination (e.g. introduction of invasive species including undesirable pathogens).

2.2 Engage appropriate participants. Treatments are interpreted and carried out responsibly, effectively, and efficiently by, or under the supervision of, suitably qualified, skilled and experienced people. Wherever possible, stakeholders and community members are invited to participate in project implementation. Where possible, use of sustainable materials and processes are incorporated into restoration projects.

2.3 Incorporate natural processes. All treatments are undertaken in a manner that is responsive to natural processes, and that fosters and protects potential for natural and assisted recovery. Primary treatments including substrate and hydrological amendments, pest animal and plant control, application of specific recovery activities, and biotic reintroductions adequately followed up by secondary treatments as required. Because the recovery period may be long (e.g. growth of riparian vegetation), interim treatments to reduce adverse effects (e.g. nutrient influxes and sediment inflows into streams) should be planned for and implemented. Appropriate aftercare is provided to any plantings or animal stock.

2.4 Respond to changes occurring on site. Adaptive management is applied, informed by the results of monitoring. This includes both corrective changes of direction to adapt to unexpected ecosystem responses and additional work as needed. In some cases, additional or new research may be required to overcome particular restoration impediments.

2.5 Ensure compliance. All projects exercise full compliance with work, health, and safety legislation. All laws, regulations, and permits that apply to the project, including those related to soil, air, water, oceans, heritage, species and ecosystem conservation, are in place.

2.6 Communicate with stakeholders. All project operatives communicate regularly with key stakeholders (preferably through a communications plan, integrated with any stakeholder engagement and citizen-science activities) to keep stakeholders appraised of progress

and optimally engaged. Communication should also meet funding body requirements.

3. **Monitoring, Documentation, Evaluation, and Reporting** Ecological restoration projects adopt the principle of observing, recording, and monitoring treatments and responses to determine whether a project is on track to meeting targets, goals, and objectives, or needs adjustment. Projects are regularly assessed, with progress analyzed to adjust treatments as required (i.e. using an adaptive-management framework). Collaborations are fostered between researchers, local-knowledge experts, practitioners, and citizen-scientists, especially where treatments are innovative or being applied at a large scale. Monitoring needs are reassessed throughout the project and resources reallocated or expanded accordingly.

3.1 Monitoring design. Monitoring to evaluate restoration outcomes begins at the planning stage by developing a monitoring plan to identify treatment effectiveness (See also Boxes 5 & 6). This plan includes specific questions to be addressed through monitoring, sampling design for collecting baseline, implementation, and post-treatment data, procedures for documenting and archiving collected data, plans for data analysis, and plans for communicating results to adapt management strategies on site and inform stakeholders of lessons learned.

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, baseline data are collected and milestones determined to gauge whether the rate of progress is on track. Additionally, "trigger points" along that path can be helpful; if the data reach a trigger, then corrective actions may be needed.

3.1.2 Monitoring methods should be appropriate to the goals of the project. Whenever possible, methods should be easy-to-use, and implemented through participatory processes. When formal quantitative sampling is needed, the sampling design must include a sufficiently large sample size to enable statistical analyses and inferences. In all cases the methods should be detailed enough to be repeatable in future years.

3.1.3 Project managers should be mindful that monitoring is essential to determine whether goals are met and also to provide learning opportunities. Involving stakeholders in project design and data collection and analysis helps improve collaborative decision-making, provides a sense of ownership and engagement, motivates stakeholders to maintain longer-term interest, and strengthens stakeholder capacity and empowerment. Any monitoring system must have built-in opportunities for learning and adaptation.

3.2 Keeping records. Adequate and secure records of all 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 session and costs, along with all evaluation monitoring records are maintained for future reference. Provenance data should include location (preferably GPS-derived) and description of donor and receiving sites or populations. Documentation should include reference to collection protocols, date of acquisition, identification procedures, and collector/propagator's name. Additionally:

3.2.1 Consideration should be given to having data be open-access, or adding results to open access repositories such as SER's Restoration Resource Center or other national or international databases; and,

3.2.2 Managers should archive data using secure storage. Metadata describing the contents of each dataset should be included.

3.3 Evaluating outcomes. Evaluation of the outcomes of the work is carried out, with progress assessed against project targets, goals, and objectives. This requires use of an evaluation tool (e.g. the Five-star System presented in this document; the Audit Tool of the Open Standards among others or conventional ecological evaluation methods).

3.3.1 Evaluation should adequately assess results from the monitoring; and,

3.3.2 Results should be used to inform ongoing management.

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

3.4.1 Reporting should convey the information accurately and accessibly, customized to the audience; and,

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

4. **Post-Implementation Maintenance**

4.1 Ongoing management. The management body is responsible for ongoing maintenance to prevent deleterious impacts and carry out post-project completion monitoring to avoid regression into a degraded state. This requirement should be considered in budgets prior

to restoration. Comparison to an appropriate reference model should be ongoing and includes:

- Periodic surveillance of the site to check for re-occurrence of degradation to protect the investment in restoration, ideally involving stakeholders;
- Protocols for action built into operations of the managing organization, working in collaboration with stakeholders as required; and,
- Continued communication about the project to new generations 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; and,
    - reinforcing lessons learned including the need to carry out similar projects elsewhere.

Section 4 — Leading Practices

Part 1. Developing Reference Models for Ecological Restoration

The practice of ecological restoration involves removing or limiting sources of degradation and assisting the ecosystem in recovering, insofar as possible, to the condition it would be in had degradation not occurred, while also accounting for anticipated change. This requires a model to predict that condition, called a reference model (Principle 3), which is constructed empirically from multiple reference sites and theoretically based on best available information. This model should account for multiple ecosystem attributes and their variation within the target ecosystem, as well as overall ecosystem complexity and dynamics (i.e. changes over time). Each of these considerations is important for establishing project goals that accurately reflect an appropriate target ecosystem. In some cases, it may be necessary to identify multiple reference models, for example, for native ecosystems that have non-equilibrium dynamics (Suding & Gross 2006) or alternative reference models where irreversible change has occurred or is anticipated. In practice, the process of building a reference model and the model's reliability will vary based on both project resources and the availability of relevant ecological information. Information may be readily available or collectable for some native ecosystems (e.g. forested areas of western North America where LiDAR data allow for creation of reference models at landscape scales; Wiggins et al. 2019), where for others reference sites and data may be scarce (e.g. threatened coastal forest ecosystems of Chile for which only a few small patches of forest remain; Echeverria et al. 2006). In most instances, stakeholders and project managers will have to navigate gaps in available information and or resources using professional judgment. In all cases, the best available information should be combined with solid investigative work (Swetnam et al. 1999) to develop optimal model(s) for predicting system condition had degradation not occurred.

Construction of reference models ideally incorporates a broad set of ecosystem attributes, including absence of threats, species composition, community structure, physical conditions, ecosystem function, and external exchanges (Principle 3). Some of these attributes, such as community structure (i.e. architecture with respect to vegetation strata, trophic levels, and spatial patterns) and species composition (i.e. types of species present) are relatively straightforward to assess, whereas others, such as ecosystem functions, are more complex, but equally important. Organisms interact with their environment and other organisms in complex ways that result in flows of energy, nutrients, water, and other materials, referred to as ecosystem functions. In addition to supporting ecological integrity, ecosystem functions provide the services required for life (e.g. food, fiber, water, medicines) and their inclusion in reference models is essential. Further, the physical attributes of ecosystems and ecological subsidies (e.g. seed propagules) that flow across ecosystems are important to consider in developing references, as they are the context in which species interactions occur.

In addition to incorporating individual ecosystem components, reference models should reflect ecosystem complexity and the relationships among ecosystem components (Green & Sadedin 2005). Ecosystems are composed of both living (biotic) and nonliving (abiotic) components that interact in complex ways. For instance, plants and soils are tightly linked through a system of bioregulation (Perry 1994). Plants directly affect the chemical, physical, and biological properties of soils. Thus, the type of plants growing in an ecosystem affects all aspects of the soils in the system. Similarly, soil chemical, physical, and biological properties affect the types of plants that grow in an area. These relationships and bioregulation are not unique to terrestrial ecosystems. In aquatic systems, primary productivity (in which energy is fixed via photosynthesis) is tightly linked with productivity at higher trophic levels and drives the overall structure of the food web (Vander Zanden et al. 2006). Although explicit consideration of the entire suite of components and interactions in an ecosystem is impossible, the reference model should be developed with the aspiration of including as many components and interactions as feasible and at minimum should include indicators for each of the key ecosystem attributes identified in Principle 3. Projects that emphasize a limited number of factors, such as those that focus on single ecosystem services, may have limited potential to restore overall ecosystem complexity. On the other hand, projects incorporating many factors into their reference models and project goals may have a greater likelihood at restoring ecosystems that ultimately protect biodiversity, deliver ecological resilience, and provide higher rates of ecosystem services over the long term.

Incorporating Historical and Future Change

Ecosystems respond to changing environmental conditions, which adds complexity to ecological restoration and other types of ecosystem management. To account for temporal change, the

reference model is conceived as the condition the target ecosystem would be in had degradation not occurred, while anticipating future change. It does not represent a condition in the past. Historical information may be useful in the construction of reference models, especially if modern reference sites are unavailable. When using historical data to develop reference models, however, consideration should always be given to the degree of background environmental change that has occurred (e.g. changes in temperature, precipitation, and soils) or is anticipated to occur (e.g. climate change), and the extent to which the reference model should be adjusted to account for these changes (see also Box 2 and Appendix 1).

Ecosystem change is driven by factors that are external to the ecosystem, such as climate, but also through successional processes and many types of ecosystems exhibit multiple successional stages. Because of this, successional stage of the restoration site must be considered when selecting reference sites. For example, late-successional ecosystems (e.g. 1,000-year-old forests) are likely unsuitable reference sites for the initial phases of restoration of early-successional forest stands, although they are useful for informing the multi-phase, long-term reference model, and setting long-range project goals. In addition, for some sites there may be multiple potential outcomes of succession, based on chance events such as natural disturbances or order of arrival of species (Chase 2003). Rather than assuming that the system will always follow a single successional trajectory, it may be useful to develop a set of reference models for multiple potential trajectories. Incorporating equilibrium dynamics into reference models clearly makes restoration planning more complex but will facilitate project success by giving managers a more informed perspective on suitable project outcomes or, when one of multiple potential stable states is desired, helping managers avoid feedbacks that would drive the system in unintended directions (e.g. managing the order of species introductions or removing species that are likely to push the system in the unintended direction; Suding & Gross 2006).

Reference Sites and Other Sources of Information

Because no two sites are identical, best practice is to use multiple reference sites and other information to develop the reference model. Inventory of one site will capture only a fraction of the species pool and be unlikely to represent the average condition of the target ecosystem. Ecosystems that are highly heterogeneous will require more reference sites than those that are more homogeneous. Due to the high degree of land alteration globally, however, many ecosystems may not have an adequate number of reference sites and practitioners may need to rely on successional models and other sources of information as detailed below.

In addition to information from reference sites, information from the site baseline survey and indirect, secondary sources of evidence may assist with determining reference conditions (Clewell & Aronson 2013; Liu & Clewell 2017). These secondary sources, although imperfect, can still effectively help guide restoration planning (Egan & Howell 2001). For instance, historical information obtained from natural archives and cultural records can provide valuable insights. One important natural archive, for example, is annual growth rings of older trees, which can reveal past incidences of drought and fire. Ancient seeds and other plant fragments cached by rodents in caves can usually be identified to species. The seed bank as well as pollen deposits in soil and sediments can be used to identify plant species that occurred at a site. Logs, large woody debris, and charcoal buried in wet soil or sediments can be excavated, identified to species, and reveal old-growth conditions that disappeared long ago. Cultural records comprising photographs (including aerial and repeat photography), landscape paintings, maps, diaries and books, and land surveys are possible sources of information about historical vegetation conditions. Older species descriptions in local floristic treatments generally include habitat information. Specimen labels in herbaria and museums identify species collected at specific sites many years ago and sometimes list other species occurring with them. Care must be taken when utilizing any of these sources of historic information, however, because historical conditions may be inadequate predictors of modern ones. Additionally, natural archives and cultural documents each have their own biases and limitations that affect inferences. Finally, few ecosystems exist for which historical conditions are fully known. Even for locations where data are available, information is limited to one or a few ecosystem components and processes.

Other information sources key for developing reference models include traditional and local ecological knowledge (TEK and LEK; e.g. Zedler & Stevens 2018), and databases and tools that characterize ecosystem properties (e.g. soil descriptions, rare species distributions). If only a few species are identifiable from these indirect sources of evidence, an ecologist familiar with the natural history of the region can frequently ascertain the estimated condition of the ecosystems if degradation had not occurred and deduce species compositions. Implementation plans can be prepared from descriptions of existing examples of those same ecosystems.

Adequate investment in developing a reference model is an important consideration in project planning and budgeting. The quality of the reference model will vary among projects, based on project resources and available sites and information. Stakeholders and project managers should aspire to create the best model possible given project constraints. Note that in some jurisdictions, reference models may have already been developed for some ecosystems.

Part 2. Identifying Appropriate Ecological Restoration Approaches

For millions of years, natural recovery processes have been autogenically repairing naturally disturbed sites in both terrestrial and aquatic environments (e.g. volcanos, landslides, glaciation, asteroid impacts, sea level changes, tsunamis, riverbank erosion; e.g. Matthews 1999). While the sequential patterns of recovery (i.e. succession) differ among ecosystems, all native species are likely to have evolved some capacity to recover after natural disturbances or stresses to which they have adapted

(Holling 1973; Westman 1978). By understanding how recovery processes operate in cases of natural disturbances, strategies for the restoration of human-caused degradation can be developed (Cairns Jr et al. 1977; Chazdon 2014). Correctly assessing the capacity of individual species to regenerate at a specific site facilitates selection of appropriate approaches and treatments, thus enabling efficient use of financial resources and other restoration inputs (McDonald 2000; Martínez-Ramos et al. 2016).

A first step in defining effective restoration strategies is to identify the constraints (sometimes referred to as "filters" or "barriers") preventing ecosystem recovery (Hobbs & Norton 2004; Hulvey & Aigner 2014). Constraints will of course include the anthropogenic causes of degradation, but also the consequences of these, such as unsuitable substrates, absence of niches, altered niches, lack of resources, herbivory, competition, lack of propagule availability, or absence of cues to break seed dormancy. By addressing the constraints that prevent recovery without introducing new ones, natural processes that have been operating over evolutionary time can be reinstated to assist the recovery of the disturbed site (e.g. revegetation from stored propagules; McDonald 2000; Prach & Hobbs 2008).

Natural regeneration, sometimes referred to as "passive" restoration, is often the most cost-effective approach when natural recovery potential is high. Where potential for natural regeneration is absent or low, however, it is usually necessary to reestablish or increase organisms or depleted populations through more active means, such as **assisted regeneration** or **reconstruction**, sometimes referred to as "active" restoration. All three of these **approaches** use natural recovery processes and require ongoing adaptive management until recovery is attained.

1 Natural (or spontaneous) regeneration. Where damage is relatively low and topsoil retained, or where sufficient time frames and nearby populations exist to allow recolonization, plants and animals may be able to recover after cessation of certain types of degradation (Prach et al. 2014; Chazdon & Guariguata 2016). This may include removal of contamination, inappropriate grazing, over-fishing, restriction of water flows, and inappropriate fire regimes. Animal species may be able to recolonize the site if there is sufficient habitat connectivity, and plant species may recover through resprouting or germination from remnant soil seed banks or seeds that naturally disperse from nearby sites (Grubb & Hopkins 1986; Powers et al. 2009). In some cases, natural regeneration can also be used even in heavily disturbed sites, such as abandoned quarries and mines, although this will likely be a long-term process (Prach & Hobbs 2008).
2 Assisted regeneration. Restoration at sites of intermediate or greater degradation requires removal of the causes of degradation and active interventions to correct abiotic and biotic damage and trigger biotic recovery (e.g. by mimicking natural disturbances or by providing key resources). Examples of abiotic interventions include: actively remediating substrate chemical or physical conditions; building habitat features such as shellfish reefs (O'Beirn et al. 2000); reshaping watercourses (Jordan & Arrington 2014) and landforms (Prach & Hobbs 2008); reinstating environmental flows and fish passage in estuaries and rivers (Kareiva et al. 2000); applying artificial disturbances to break seed dormancy (Mitchell et al. 2008); and, installing habitat features such as hollow logs, rocks, woody debris piles, soil microniches, and perch trees (Elgar et al. 2014; Castillo-Escrivà et al. 2019). Examples of biotic interventions include: controlling invasive species (Saunders & Norton 2001; Chazdon et al. 2017); supplementary **reintroduction** of species that cannot migrate into the restoration area without assistance (e.g. **rewilding** of animals or reintroduction of tree species with very large seeds); and, the **augmentation** or **reinforcement** of depleted populations of species where genetic diversity is insufficient (see also Appendix 1).
3 Reconstruction. Where damage is high, not only do all causes of degradation need to be removed or reversed and all biotic and abiotic damage corrected to suit the identified native reference ecosystem, but also all or a major proportion of its desirable biota need to be reintroduced wherever possible (Bradshaw 1983; Seddon et al. 2004). 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), earlier successional species may need to be reintroduced earlier than later successional species (Temperton et al. 2004). In ecosystems that do not exhibit these successional patterns, however, all species may need to be introduced from the outset (e.g. Rokich 2016).

A mosaic of the three approaches may be warranted and mapped where there are different degrees of degradation across a site, or as a technique to increase efficiency and lower costs (Bradshaw 1983; Walker 2011), especially at larger scales. That is, some parts of a site may require a natural regeneration approach, others may require an assisted regeneration approach, and still other areas may require a reconstruction approach, or combinations as appropriate. One combined approach is **applied nucleation**, which involves planting small patches of vegetation (often trees) that attract dispersers and facilitate establishment of new recruits, expanding the forested area over time. Applied nucleation has shown promise in restoring landfills (Corbin et al. 2016), Mediterranean woodlands (Rey Benayas et al. 2008), tropical forests (Corbin & Holl 2012; Holl et al. 2017), and other ecosystems. Deciding on an appropriate approach or combination may not be self-evident. Knowledge and experience are important in assessing the degree of natural regeneration potential present, and whether that potential may respond to particular forms of assistance (and in a timely way). Where specific knowledge is unavailable, an adaptive management approach to understanding the effectiveness of different types of regeneration is appropriate (e.g. allowing a couple of years to assess the rate of natural regeneration prior to deciding the best approach; Holl et al. 2018). Responding to site conditions in this way will ensure optimal levels of similarity between

the restoration outcome and conditions defined by the reference model.

Part 3. The Role of Ecological Restoration in Global Restoration Initiatives

Within the last 30 years, ecological restoration has grown from implementation at the small-patch scale to a primary strategy for conserving biodiversity and improving human wellbeing across large landscapes. When the vision of restoration exceeds small-patch scales, the goals and approaches of restoration must be scaled up (Principle 7). Landscape patterns (spatial relationships of ecosystem types) and landscape-level processes (e.g. water flow, erosion, nutrient fluxes, land-use changes) are important attributes to consider (Holl et al. 2003). At large scales, the greater diversity of ecosystems, stakeholders, and land uses create competing goals, but may also precipitate common solutions. Consequently, restoration at this scale must focus on providing multiple, complementary, and integrated benefits for ecosystems and stakeholders.

Global Restoration Initiatives

Growing awareness of the need for environmental and socio-cultural repair has led to a global ramping up of ecological restoration and allied restorative activities (Introduction, Principle 7). However, land degradation has continued mostly unabated, and the need to both avoid and counter the effects of this degradation is increasingly more urgent. Toward this end, several large-scale restoration initiatives and agreements have been launched at the global scale that promote a wide range of **ecosystem management** and **nature-based solutions** (Box 10). Within many of these initiatives and agreements restoration is broadly defined (e.g. Forest Landscape Restoration) and includes all activities along the restorative continuum (Principle 8). These initiatives largely focus on improving the ecological health and productivity of landscapes to support the current and future wellbeing of people, protect biodiversity, reduce disaster risk, and mitigate and adapt to climate change. For some initiatives, restoration is seen as a method to improve access to and sustainability of natural resources. Others recognize the potential of restoration to catalyze rural economies, provide jobs and income, and improve food and water security, among other objectives. These outcomes are not necessarily mutually exclusive. In fact, when fair access to and sustainable use of natural resources is an outcome of large-scale restoration programs, several other global objectives are also achieved.

Landscape Restoration Approaches

Many large-scale restoration initiatives include opportunities to employ landscape restoration approaches. Landscape restoration involves practices based on the principles of both landscape ecology and landscape sustainability science (LSS; Frazier et al. 2019), in which a "landscape" is seen as a social–ecological system. LSS focuses on improving the dynamic relationship between ecosystem services and human wellbeing in changing social, economic, and environmental conditions. Consistent with the definition of landscape sustainability (Wu 2013), **landscape restoration** can be defined as a planned process that seeks to recover landscape-level ecological integrity and the capacity of a landscape to provide long-term, landscape-specific ecosystem services essential for improving human wellbeing. Accordingly, landscape restoration involves both ecological and social targets and goals (Principle 1). Additional approaches to large-scale restoration include the concept of **Sustainable Multifunctional Landscapes**, which are "landscapes created and managed to integrate human production and landscape use into the ecological fabric of a landscape maintaining critical ecosystem function, service flows and biodiversity retention" (O'Farrell & Anderson 2010).

Conducting landscape restoration activities requires an in-depth understanding of landscape composition, structure, and function, and the link between ecological integrity and meeting human needs (Wu 2013). These landscape attributes vary from those that are considered for ecological restoration at the site-level (composition, structure, function, at the ecosystem or community level, as well as lower levels [species, genes] of the biological hierarchy; Principle 7). Landscape restoration involves considerations at levels of the biological hierarchy above the ecosystem scale and an explicit consideration of the types and proportions of ecosystems within the landscape, the spatial organization of the units, and the link between landscape composition, structure and functions. Restoring functions, flows of energy, nutrients, and other subsidies through the landscape may be equally as important as restoring composition and structure in some cases, especially for the delivery of particular ecosystem services. For example, restoring hydrological processes and water movement among ecosystems is critical for stream-flow regulation, which is one of the ecosystem services that often drives interest in restoration.

Planning and executing landscape-scale restoration projects requires landscape-scale assessment of ecological degradation and restoration needs at the same scale, including biodiversity and ecosystem services and the tradeoffs between them. Landscape restoration activities should be concentrated in strategic locations, with ecological and social benefits balanced (Doyle & Drew 2012), and delivered throughout entire watersheds and beyond (IUCN and WRI 2014; Liu et al. 2017).

Governments are often involved in landscape restoration programs with coalitions of local administrations and stakeholder groups. Stakeholder engagement platforms are built for several important reasons, including to develop a sense of responsibility for the landscape and to emphasize how different stakeholders view the potential of restoration and its costs and benefits. However, unless stakeholder-driven processes are consistent with the concepts of landscape sustainability science, key trade-offs between stakeholder-desired services, biodiversity, and ecological integrity may not be considered and landscapes may be further degraded. Managing tradeoffs to maximize landscape sustainability is critical, as the long-term effectiveness of national restoration programs requires consideration of the

Box 10. Global restoration initiatives

• United Nations (UN) Sustainable Development Goals (SDGs) for 2030 call for the restoration of marine and coastal ecosystems (Goal 14), as well as forests and other ecosystems that have been degraded (Goal 15). On March 1, 2019 in support of a broad range of the SDGs and many of the initiatives below, the United Nations General Assembly declared 2021–2030 the Decade on Ecosystem Restoration. The UN Environmental Programme (UNEP), Food and Agriculture Organization (FAO), Global Landscapes Forum (GLF), and International Union for Conservation of Nature (IUCN), among others, are expected to lead implementation and knowledge exchange programs for the Decade on Ecosystem Restoration.

• The Convention on Biological Diversity (CBD) has a target of restoring 15% of degraded ecosystems by 2020 to mitigate the impacts of climate change and to combat desertification (Aichi Biodiversity Target 15), and views ecological restoration as key to delivering essential ecosystem services (Aichi Biodiversity Target 14). The CBD has adopted a Short-Term Action Plan on Ecosystem Restoration (CBD 2016), and restoration is expected to play an even larger role as the current biodiversity targets expire and are revised for the post-2020 biodiversity framework. The CBD (2018) also encourages Parties to further strengthen their efforts "… to identify regions, ecosystems and components of biodiversity that are or will become vulnerable to climate change … to promote ecosystem restoration and sustainable management post-restoration."

• The United Nations Convention to Combat Desertification (UNCCD) promotes land restoration and rehabilitation as part of the UNCCD strategic framework 2018–2030, and specifically to achieve Land Degradation Neutrality (LDN; Orr et al. 2017), wherein, "the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems" (UNCCD 2017). Current drylands and future drylands under climate change will be highly vulnerable, requiring a stronger collaboration across the three Rio Conventions (CBD, UNCCD, United Nations Framework Convention Climate Change [UNFCCC]) on how to avoid, reduce and reverse land degradation with the support of sustainable land management practices, while considering the special mandates of each Convention (Akhtar-Schuster et al. 2017; Chasek et al. 2019).

• The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) promotes "land restoration", including activities such as restoring agricultural productivity, adopting agricultural best practices, and other sustainable utilization activities. The IPBES Global Assessment on Biodiversity and Ecosystem Services (https://www.ipbes.net/global-assessment-biodiversity-ecosystem-services) reports that about 1 million animal and plant species are now threatened with extinction, many within decades, more than ever before in human history. Loss of biodiversity is shown to be not only an environmental issue, but also a developmental, economic, security, social, and moral issue. Restoration and land-based climate change mitigation actions are viewed as key elements of the transformative change needed to avert mass extinctions and the subsequent loss of ecosystem services.

• The largest and most diverse initiative for large-scale restoration is the Bonn Challenge, launched by the Government of Germany and the International Union for Conservation of Nature (IUCN), and later endorsed and extended by the New York Declaration on Forests (Goal 5). This global effort seeks to bring 150 million hectares of deforested and degraded land into restoration by 2020 and 350 million hectares by 2030. The Bonn Challenge has galvanized high-level national and subnational commitments from 58 governments and land managers, totaling over 170 million hectares, to assess opportunities for, and implement restorative activities using the Forest Landscape Restoration (FLR) approach.

• In support of the Bonn Challenge, several regional initiatives help bring countries together to share commitments, knowledge, tools, and capacities regarding FLR. In Latin America this includes the 20×20 initiative, which seeks to bring into restoration 20 million hectares of degraded land by 2020. Similarly, The African Forest Landscape Restoration Initiative (AFR100) is a country-led effort to bring into restoration 100 million hectares of degraded land by 2030. Both 20×20 and AFR100 have exceeded their commitment goals. The 17 countries supporting the Bonn Challenge through 20×20 have committed 50 million hectares and the 28 countries supporting AFR100 have committed 113 million hectares to date. In addition to these initiatives, there are budding regional platforms emerging in the Caucuses and Central Asia, Europe, and Southeast Asia, and many other large-scale commitments to FLR throughout the rest of the world at both the national and subnational scale.

• Additional restorative activities are proposed or promoted as part of REDD+ (Reduce Emissions from Deforestation and Forest Degradation) projects at national and sub-national levels, as part of Nationally Determined Contributions (NDCs) to the UNFCCC, by the Global Landscapes Forum, and across thousands of projects at local, regional, and national scales throughout the world.

needs of future generations, and options for enhancing future sustainability under climate change.

Decision-support tools can help define and map degradation, set restoration objectives, discern trade-offs and synergies among potential restoration actions or approaches, and identify restoration opportunities (IUCN and WRI 2014; Hanson et al. 2015; Chazdon & Guariguata 2018; Evans & Guariguata 2019). Further, integrating biodiversity information,

species-distribution modeling, and habitat-suitability modeling at landscape scales can identify areas where ecological restoration may reduce threats to species or actively restore their populations or habitat (Beatty et al. 2018). Moreover, economic analyses and scenarios based on ecosystem service supply and biodiversity benefits can contribute to understanding the cost-effectiveness and total costs of specific restoration actions in particular areas. Additional decision-support tools are critically needed, however, for assessing delivery of selected ecosystem services, tradeoffs between ecological and social outcomes, and social-economic outcomes such as livelihoods and food security (Beatty et al. 2018).

One important way to advance the science, practice, and policy of landscape restoration is to develop and promote bilateral and multilateral cooperation among and within countries. A bibliometric analysis shows a significant increase in publications on ecological restoration in developing countries (e.g. China and Brazil between 1988 and 2017; Guan et al. 2019). Experience and expertise sharing, co-financing, and co-developing new knowledge for more effective policy and practice should be encouraged among regions (Liu et al. 2019), and **south–south cooperation** is equally important for knowledge sharing in developing and newly industrialized countries (Liu et al. 2017).

Forest Landscape Restoration (FLR), the main approach behind the Bonn Challenge and other global restoration initiatives, has increased awareness of the need for restoration and allied restorative activities at the landscape scale. However, the activities implemented under Forest Landscape Restoration are not necessarily equivalent to ecological restoration—a situation that has contributed to confusion about restoration as a concept. Although FLR is defined as "a process that aims to regain ecological functioning and enhance human well-being in deforested or degraded landscapes" (Besseau et al. 2018), ecological restoration is only one of many activities in FLR. In fact, FLR programs comprise a range of activities aligning with the "Restorative Continuum" described in Principle 8 (i.e.reduced impacts, remediation, rehabilitation, ecological restoration), including the conservation of existing protected areas and increasing sustainability in areas of primary economic production. Importantly, FLR does not necessarily place a higher value on one type of activity within the continuum than another. Ecological restoration, for instance, is not viewed as an inherently better option than conservation agriculture or agroforestry. However, many FLR practitioners view ecological restoration as a key component of every FLR project. These practitioners recognize that areas primarily devoted to economic production, especially degraded agricultural landscapes, have enormous social, economic, and ecological needs for intervention. Application of an integrated, holistic approach to conserve and repair ecosystems is most likely to achieve direct improvements in human wellbeing effectively and equitably, an approach similar to that of the UNCCD's Landscape Degradation Neutrality program. The selection of activities within FLR, however, is based on many factors, including how the action mitigates degradation as well as how it may support stakeholder-defined objectives (e.g. climate resilience, food and water security, biodiversity conservation). FLR has been interpreted in different ways (Mansourian 2018) leading to different constructs of FLR (e.g. safeguarding biodiversity, reducing land degradation, supporting sustainable timber production). Transparency and clear communication, along with flexibility to implement a diversity of restoration activities in a landscape, are thus key to successful implementation.

Broad political support exists for FLR and the Bonn Challenge, which are important implementation mechanisms for the Rio Conventions (CBD, UNCCD, UNFCCC), as well as the United Nations Sustainable Development Goals and many national, continental, and regional initiatives. FLR has allowed countries and other actors to view ecosystem and landscape repair through the many different social, economic, and ecological lenses it provides. FLR has already made significant contributions to the Aichi Targets (Beatty et al. 2018). In addition, engagement of high-level policymakers at Bonn Challenge Ministerial events has resulted in support for the UN Decade on Ecosystem Restoration (2021–2030). Concern that FLR be restorative, and not create perverse incentives and collateral damage, have led to development of FLR Principles that call for restoration for multiple functions together, and maintenance and enhancement of native ecosystems (Box 11).

Conclusion

The world is entering an era of ecological restoration with governments across the globe making impressive commitments to restore degraded lands and landscapes through a wide range of restorative activities including ecological restoration at both the ecosystem and landscape scale. Ecological restoration is increasingly recognized as a critical tool for mitigating and adapting to the effects of environmental disasters and the impacts of climate change. It supports a process that improves human wellbeing at individual, community, and national levels. When implemented effectively, ecological restoration can achieve profound ecosystem services benefits, ranging from the most basic needs like improving food and water security, to reducing the spread of disease, and improving individual physical, emotional, and mental health. Ecological restoration must also be integrated with conservation and sustainable production. Restoration can help us move, globally, from centuries of cumulative environmental damage, to land degradation neutrality (Box 10), and eventually to net ecological improvement. Ecological restoration therefore promises a net gain in extent and functioning of native ecosystems, together with the delivery of critical human wellbeing benefits. Achieving this requires the support of stakeholders everywhere, and a global commitment to and investment in all types of restorative activities. This investment must be based on a strong, defensible, and understandable scientific foundation, as outlined within these restoration principles and standards.

Glossary of Terms

This glossary is adapted and expanded from McDonald et al. (2016*a*, 2016*b*).

Box 11. FLR principles.

The members of the Global Partnership on Forest and Landscape Restoration have re-articulated and strengthened a streamlined set of long-held FLR principles below (Besseau et al. 2018).

- Focus on landscapes—FLR takes place within and across entire landscapes, not individual sites, representing mosaics of interacting land uses and management practices under various tenure and governance systems. It is at this scale that ecological, social and economic priorities can be balanced.
- Engage stakeholders and support participatory governance—FLR actively engages stakeholders at different scales, including vulnerable groups, in planning and decision-making regarding land use, restoration goals and strategies, implementation methods, benefit sharing, monitoring and review processes.
- Restore multiple functions for multiple benefits—FLR interventions aim to restore multiple ecological, social and economic functions across a landscape and generate a range of ecosystem goods and services that benefit multiple stakeholder groups.
- Maintain and enhance natural ecosystems within landscapes—FLR does not lead to the conversion or destruction of natural forests or other ecosystems. It enhances the conservation, recovery, and sustainable management of forests and other ecosystems.
- Tailor to the local context using a variety of approaches—FLR uses a variety of approaches that are adapted to the local social, cultural, economic and ecological values, needs, and landscape history. It draws on latest science and best practice, and traditional and indigenous knowledge, and applies that information in the context of local capacities and existing or new governance structures.
- Manage adaptively for long-term resilience—FLR seeks to enhance the resilience of the landscape and its stakeholders over the medium and long-term. Restoration approaches should enhance species and genetic diversity and be adjusted over time to reflect changes in climate and other environmental conditions, knowledge, capacities, stakeholder needs, and societal values. As restoration progresses, information from monitoring activities, research, and stakeholder guidance should be integrated into management plans.

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

Activity: See **Restoration activities**, **Restorative activities**.

Adaptive management: An ongoing 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.

Afforestation: The process of introducing forest in an area where forest did not formerly exist in the historical past.

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.

Applied nucleation: A strategy that uses the establishment of small patches of vegetation (often trees or shrubs) or populations of animals (e.g. corals, oysters) to serve as focal areas for ecosystem recovery by enhancing colonization.

Approach (to restoration): The generic category of treatment (e.g. natural or assisted regeneration, reconstruction).

Assisted regeneration: An approach to restoration that focuses on actively triggering any natural regeneration capacity of biota remaining on site or nearby as distinct from reintroducing the biota to the site or leaving a site to regenerate. While this approach is typically applied to sites of low to intermediate degradation, even some very highly degraded sites have proven capable of assisted regeneration given appropriate treatment and sufficient time frames. Interventions include removal of pest organisms, reapplying ecological disturbance regimes and installation of resources to prompt colonization.

Attributes: See **Key ecosystem attributes**.

Augment, Augmentation (of depleted populations): (also known as enhancement, enrichment, 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.

Biodiversity: The variability among 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 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 buildup). This may occur naturally or be the result of actions to reduce the impacts of climate change.

Climate envelope: The climatic range in which the populations of a species are distributed. With climate change, the geographic locations of such envelopes are likely to shift.

Climate readiness: Refers to a circumstance where restored genetic material has been selected, on the basis of climate science and genetics, to improve a species' likelihood of persisting under anticipated 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 all 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 flow of ecosystem services.

Desirable species: Species from the reference ecosystem (or sometimes nonnative nurse plants) that will enable the native ecosystem to recover. The corollary of desirable species is undesirable species, which are often but not exclusively nonnative species.

Destruction (of an ecosystem): When degradation or damage removes all macroscopic life, and commonly ruins 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.

Ecological restoration: The process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed. (Ecosystem restoration is sometimes used interchangeably with ecological restoration, but ecological restoration always addresses biodiversity conservation and ecological integrity, whereas some approaches to ecosystem restoration may focus solely on the delivery of ecosystem services.)

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 in water bodies or on land in which the components 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 integrity: The ability of an ecosystem to support and sustain characteristic ecological functioning and biodiversity (i.e. species composition and community structure). Ecological integrity can be measured as the extent that a community of native organisms is maintained.

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 management: A management approach that relies on the integration of scientific knowledge of ecological relationships within a complex sociopolitical and values framework toward the general goal of protecting native ecosystem integrity over the long term.

Ecosystem resilience: The degree, manner and pace of recovery of ecosystem properties after natural or human 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 services: The direct and indirect contributions of ecosystems to human wellbeing. They include production of clean soil, water, and air; moderation of climate and disease; nutrient cycling and pollination; 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 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.)

Forest Landscape Restoration (FLR): A process that aims to regain ecological functioning and enhance human wellbeing in deforested or degraded landscapes, and which can incorporate one or more allied activities alongside ecological restoration. FLR should not cause collateral damage to biodeversity.

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. At the point of self-organization, the restoration phase could be considered complete and management shifts to a maintenance phase.

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.

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 native populations can have negative impacts, such inbreeding depression.

Germplasm: The various regenerative materials of plants and animals (e.g. embryos, seeds, vegetative materials) that provide a source of genetic material for future populations.

Green infrastructure: A network of natural or seminatural features (e.g. wetlands, healthy soils, and forest ecosystems, snowpack) that can help increase ecosystem services.

Inbreeding depression: The reduced biological fitness in a given population as a result of inbreeding, or breeding of related individuals.

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): 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 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. Exchanges are facilitated by habitat linkages.

Landscape restoration: A planned process that seeks to recover landscape-level ecological integrity and the capacity of a landscape to provide long-term, landscape-specific ecosystem services essential for improving human wellbeing.

Local Ecological Knowledge (LEK): 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.

Local provenance area or zone: A propagule collection area within which propagule transfer is thought to likely conserve locally adapted traits.

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.

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), nonrenewable (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 return to 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 application of natural regeneration or assisted regeneration approaches to ecological restoration.

Natural regeneration: Germination, birth, or other recruitment 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 only on increases in individuals following removal of causes of degradation, as distinct from an **assisted regeneration approach**.

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

Outbreeding depression: When offspring from crosses between individuals from different populations have lower fitness than progeny from crosses between individuals from the same population.

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.

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

Productivity: The rate of generation of biomass from the growth and reproduction of plants and animals.

Propagule: Any material that functions in propagating an organism. Propagules are produced by plants, animals, fungi, and microorganisms.

Reclamation: The process of making severely degraded land (e.g. former mine sites or wastelands) fit for cultivation or a state suitable for some human 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.

Recruitment: Production of a subsequent generation of organisms. This is measured not by numbers of new organisms alone (e.g. not every hatchling or seedling) but by the number that develop as independent 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 nondegraded version of the 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, and 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 historic 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**, a**ssisted 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 biodiversity and integrity of a designated native reference ecosystem.

Reinforcement: The intentional movement and release of an organism into an existing population of conspecifics. Reinforcement aims to enhance population viability, for instance by increasing population size, by increasing genetic diversity, or by increasing the representation of specific demographic groups or stages. This definition is very similar to and sometimes treated as synonymous with **augmentation**.

Reintroduction: Returning biota to an area where it previously occurred.

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.

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 inter-related 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. The restorative continuum includes four major categories of restorative activities that each include a further six categories of activities as explained in Principle 8.

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.

Rewilding: The planned reintroduction of a plant or animal species and especially a keystone species or apex predator (such as the gray wolf or lynx) into a habitat from which it has disappeared (as from hunting or habitat destruction) in an effort to increase biodiversity and restore the health of an ecosystem.

Scientific discovery: Knowledge obtained from a structured, logical approach, based on systematic observation, measurement, and the formulation, testing, and modification of ideas (hypotheses).

Seed transfer zone: A defined geographic area within which seeds are predicted to be able to be moved without adverse fitness effects.

Selfing: Self-fertilization; self-pollination.

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

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 outside 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.

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.

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 infraspecific 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 government representatives, businesses, scientists, landowners, and local users of natural resources.

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.

Succession (ecological): The process or pattern of replacement or development of an ecosystem after disturbance.

Sustainable multifunctional landscapes: Landscapes created and managed to integrate human production and landscape use into the ecological fabric of a landscape maintaining critical ecosystem function, service flows and biodiversity retention.

Target: The specific ecological and social outcomes sought at the end of the project, including the native ecosystem to be restored.

Threat: A factor potentially or already causing degradation, damage or destruction.

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 (TEK): 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.

Translocation: The intentional transporting (by humans) of organisms to a different part of a given landscape or aquatic environment or to more distant areas. The purpose is generally to conserve an endangered species, subspecies or population.

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

Wellbeing: 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:

Supplement S1. Historical principles and concepts of ecological restoration and allied activities.

Appendix 1

Selection of seeds and other propagules for restoration

This appendix is adapted and expanded from McDonald et al. (2016a). While there are many considerations to be made when deciding on the selection of plant seeds and other **propagules** (e.g. vegetative material, spores, eggs, live young) for restoration projects, genetic considerations can be paramount to ensure the resulting populations successfully reproduce and persist. These considerations are particularly important in fragmented landscapes, especially under climate change.

Genetic considerations for sourcing seeds or other propagules[3]

Restoration practitioners have widely adopted the concept of confining propagule collection to a **local provenance area** or **seed-transfer zone** to ensure that propagules selected for restoration are locally adapted. However, the protocol of only collecting propagules very close to the restoration site is now considered an inappropriate interpretation of local provenance, as geographic distance may not be a good measure of ecological differences among sites. That is, many practitioners now understand that the degree of local adaptation varies by species, population, and habitat (Gibson et al. 2016), and a "local" genotype may occur over narrow or broad areas (i.e. from 10s to 100s of km^2), depending on the species and its biology. For example, annual plants that are highly **selfing** with gravity-dispersed seed and historically occurring in discrete, isolated populations are predicted to have more restricted local ranges than plants with wind, water, or animal-dispersed seed, especially those that have experienced recent range expansion (Hufford & Mazer 2003; Broadhurst et al. 2008). Furthermore, in a largely degraded landscape, small fragments are at risk of elevated inbreeding when populations drop below species-specific threshold numbers. Because inbreeding depression may reduce the function and adaptation of populations, it is generally best to collect propagules from larger, higher-density populations. This means that in fragmented landscapes where populations are smaller, less dense and more isolated, collecting propagules from wider distances and multiple sources (and potentially multiplying them in production areas) may be necessary to capture sufficient

[3]For plants, we refer to seeds as the primary propagules used in restoration, but sometimes seeds are not used. Some plants produce very few seeds and are propagated more often by cuttings, divisions, or micropropagation. While the genetic principles regarding provenancing are similar regardless of propagule type, it is important to remember that genetic diversity is limited when vegetative propagation methods are used and this might affect a population's ability to respond to future adaptive challenges. This general principle is also true for some animals, such as corals, or fungi, where pieces of individuals or colonies are used as propagules in place of spores, eggs, or other modes of sexual reproduction.

genetic diversity and sufficient propagules to rebuild functional, resilient communities.

When sourcing propagules more widely, one must consider the risks of **outbreeding depression**. Although not as common as **inbreeding depression**, it can occur when species from genetically divergent populations are crossed. In some cases, fitness loss is due to a loss of local adaptation. If the parents are adapted to different conditions, the resulting offspring may be poorly adapted to either parental site. In other cases, co-adapted gene complexes can be broken up, resulting in fitness loss (Rogers & Montalvo 2004). Outbreeding depression can be particularly severe in plants when populations of different ploidy (the number of chromosomes in the cells) are combined in restorations or in seed-production areas. Ploidy differences are relatively common in both Poaceae and Asteraceae—two families used widely in restoration (Kramer et al. 2018) and populations with differing ploidy levels can be found in close proximity (Gibson et al. 2017). Because populations of different ploidy should not be mixed in nursery production or restoration, testing via flow cytometry may be required to determine a population's ploidy levels prior to mixing, if a mixing strategy is desired. Outbreeding depression in animals has not been as widely identified as in plants, but it exists (e.g. Sagvik et al. 2005; Huff et al. 2011).

Propagule sourcing and climate change

The climate range in which a species currently exists is known as its climate "niche" or "envelope." As the climate changes, this **climate envelope** is likely to uncouple from a species' current range and, where conditions become hotter, may move further poleward or to higher elevations. Climate envelopes may also be affected by changes in rainfall with areas becoming drier or wetter. However, because precipitation is likely to change in less predictable ways than temperature, it is likely that the displacement of climate envelopes will be more complex. These changes may also affect individual populations of a species at differential rates.

Although many species have endured climate changes in the past, the rate of current climate change, as well as fragmentation and anthropogenic barriers to migration, are unprecedented and challenge species survival. We cannot precisely predict the type and scale of risks that ecosystems face because only a small proportion of species have been individually studied. We know that some species or populations may be lost from their current locations, with some becoming locally or regionally extinct due to barriers to migration and other factors. Others will colonize new areas, altering local species assemblages. Some may have sufficient "adaptive plasticity" to persist as climates change, as has been demonstrated from **translocation** experiments. That is, an individual plant may be able to adjust its form by mechanisms such as reducing its leaf size, increasing leaf thickness or altering flowering and emergence times. Animals may alter feeding choices (e.g. omnivorous bear species switching foods to plants more resilient to climate change). Generalist species of fauna will generally survive climate change better than specialist species. In most cases, persistence may depend on a species' capacity for adaptation, which in turn depends on the size and genetic diversity of individual populations.

Many factors will influence a species' ability to adapt to new conditions or to migrate, including patterns of gene flow, geographic distribution of the species, the heterogeneity of the habitat and climate where the species occurs, and other biotic and abiotic factors, including whether the species is an early successional or late successional species. Species of flora or fauna that have large populations, high genetic diversity, long-distance gene flow, and naturally high reproductive and dispersal capabilities may have a higher chance of adapting or migrating as their climate envelope moves. Conversely, species or populations with less genetic diversity and low dispersal capabilities that occur in isolated patches or that have become isolated through anthropogenic disturbance may be less able to adapt or migrate in response to climate change.

Landscape history also plays a role in the likelihood of adaptation. For example, for some highly biodiverse "old, climatically buffered infertile" landscapes (or "OCBILs" sensu Hopper 2009), there is every likelihood that species have resisted climate impacts from multiple climate shifts without glaciation. As a result, species have persisted on these landscapes over geological time through adaptation to moisture and temperature fluctuations. Therefore, in OCBILs such as much of Australia and southern Africa, species exhibit a high level of pre-adaptation to climate swings. Extinction and local extirpation of species in OCIBIL landscapes are more often due to fragmentation and habitat loss. In contrast, in temperate regions many species are adapted to long-distance migration, such as occurred following deglaciation.

Tools and Future Directions

Protocols for the selection of propagules to enhance a species' adaptive potential in restoration projects are being developed. Restoration activities to enhance adaptive potential may be unnecessary in large, intact habitats because of high connectivity among populations. Actions to assist genetic adaptation will likely be beneficial for fragmented landscapes or those likely to become fragmented due to climate change. Although the local gene pool will play a major role in adaptation, it may be prudent to include some germplasm of the same species from a predicted "future climate"—that is, a region with a climate similar to that predicted for the area being restored. Suggestions for sourcing plant seeds either conservatively or when a more expansive approach is appropriate are provided in Table A1. Researchers are encouraged to design protocols for trials or formal experiments integrated into low-risk restoration settings.

Tools are available to help restoration planners undertake **climate readiness** analysis at the planning stage. First, restoration practitioners are encouraged to seek predictions of climate-change effects on ecosystems where they work. Second, practitioners are encouraged to seek further information and collaborate with researchers to gain a better understanding of predicted responses of species to fragmentation and climate change and to identify the relative risks of options relating to the deliberate movement of genetic material in restoration

Table A1. Where a plant or animal lies along a spectrum of species and habitat characteristics can assist propagule sourcing decisions (modified from Havens et al. 2015).

More conservative/local propagule sourcing	*Species characteristics*	*More relaxed/longer distance propagule sourcing*
Narrowly distributed including edaphic endemics	⟷	Widely distributed
Taxonomic uncertainty (potential for cryptic species)	⟷	Taxonomic stability (well-studied)
Little long-distance gene flow	⟷	Extensive long-distance gene flow
	Habitat characteristics	
Historically fragmented	⟷	Recently fragmented
High quality	⟷	Highly degraded
Ancient or stable landscape	⟷	Young or dynamic landscape

projects. For plants, common-garden studies are key to understanding the risks and benefits of plant-material movement. Third, web-based tools are becoming increasingly accessible in some countries for identifying whether the species, or population, currently occurring near the restoration site will still be suited to climates predicted to occur at the site in the future. In North America, the Seedlot Selection Tool (https://seedlotselectiontool.org/sst/) is proving very useful for plants, and in Australia, the Atlas of Living Australia website (www.ala.org.au) can help practitioners identify the natural geographic range of a species and whether it may have potential to tolerate the conditions predicted to occur under climate change scenarios, which themselves are mapped on the website www.climatechangeinaustralia.gov.au (see Booth et al. 2012).

Many restoration projects are already sourcing plant seeds from more distant provenances, often with climate change in mind. Proposed propagule sourcing strategies to build climate-readiness into restoration through ensuring genetic diversity include: *relaxed local provenancing* (Kaye 2001); *composite provenancing* (Broadhurst et al. 2008); *admixture provenancing* (Breed et al. 2013); *predictive provenancing* (e.g. Crowe & Parker 2008); and *climate-adjusted provenancing* (Prober et al. 2015; Fig. A1). Descriptions of each strategy along with the benefits, risks, and most appropriate uses are in Table A2. Application of any such strategy should be undertaken only when justified, supported by sound science within a risk-management framework that considers the potential negative effects of inbreeding and outbreeding depression. It should also include long-term monitoring (i.e. at least a decade) to record lessons to be shared with both practitioners and scientists.

Practitioners designing planting lists need to bear in mind, however, that it is impossible to be certain of the changes that will occur. Different species and populations will respond to climate change in different ways and currently there is no reliable or easy way to predict this. Furthermore, temperature and rainfall are not the only important predictors. A range of physical (e.g. substrates) and biological factors (e.g. dispersal)—which themselves may or may not be affected by a changing climate—can also have important roles in influencing the distribution of a species. While some caution will always be required, an empirical approach of testing different provenancing approaches in many areas around the world will help determine best practices. Every restoration project can be an

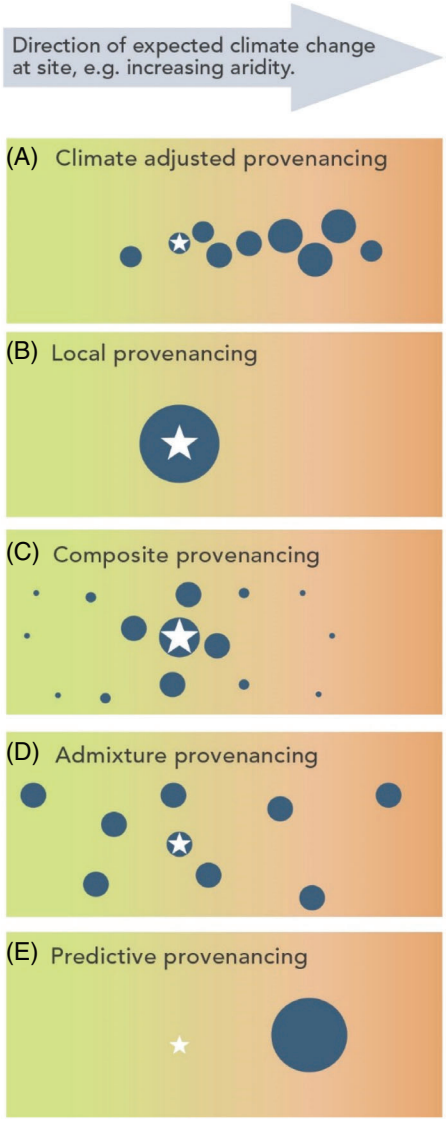


Figure A1. Provenancing strategies for revegetation (reprinted from Prober et al. 2015). Stars indicate sites to be revegetated and circles represent native populations used as germplasm sources. Circle size indicates the relative quantities of germplasm included from each population at the revegetation site. Note that climate-adjusted provenancing is not considered in Table A2.

Table A2. Types of propagule sourcing, with their description, benefits, risks, and most appropriate uses. Modified from Havens et al. (2015) and Breed et al. (2013).

Propagule sourcing type	*Definition*	*Benefits*	*Risks*	*Best Used When*
Strict local provenancing	Using propagule only from the site where restoration is occurring or populations within normal gene flow distance	• Little risk of maladaptation (at least short term)	• Narrow genetic base • Possible inbreeding • Genetic drift • Lack of adaptive potential	• Disturbance is minimal • Large local population present at or adjacent to restoration • Predicted distribution change is low
Relaxed local provenancing	Mixing propagules from geographically close populations with a focus on matching environment of source and recipient sites	• Little risk of maladaptation (at least short term) • Avoids inbreeding • Increases adaptive potential	• Can have narrow genetic base • Lack of adaptive potential for the longer term	• Disturbance is minimal • Predicted distribution change is low
Composite provenancing	Mixing propagules from populations of close and intermediate distance (or environmental match) to mimic long distance gene flow	• Avoids inbreeding • Increases adaptive potential	• Maladaptation • Outbreeding depression	• Disturbance is minimal • Fragmentation is high • Predicted distribution change is moderate
Admixture provenancing	Mixing propagules from many populations of varying distances throughout the range of the species	• Highest adaptive potential	• Largest risk of maladaptation • Outbreeding depression • Possibly invasive genotypes	• Disturbance is high • Predicted distribution change is high
Predictive provenancing	Using genotypes adapted to predicted conditions (e.g. 2050 climate projections) based on models and transplant experiments	• Deals best with changing conditions, if predictions are correct	• Projections may be wrong • Requires much research (high initial cost), although tools can help	• Disturbance is low to moderate • Predicted distribution change is high and well understood

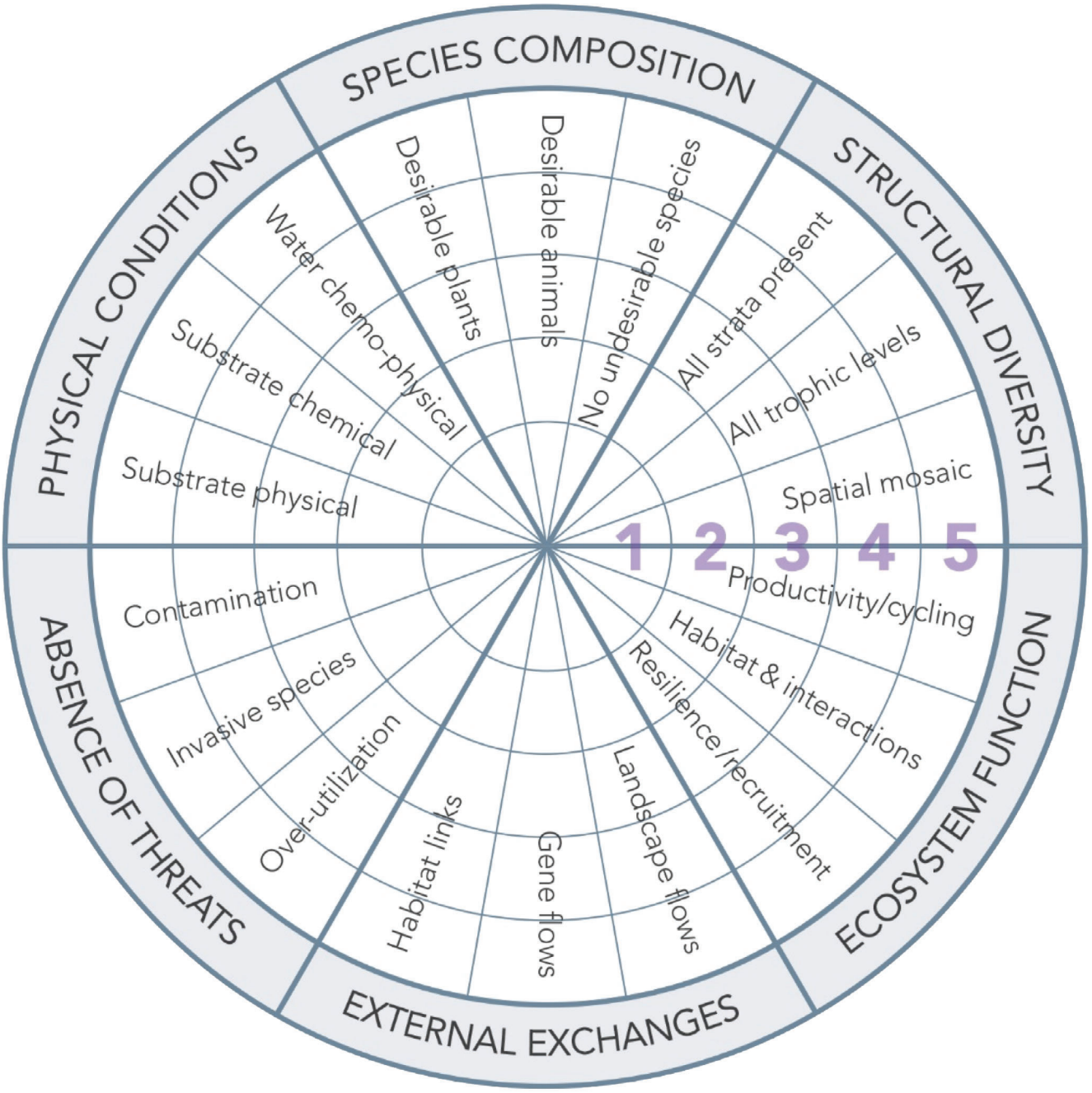
experiment if good records are maintained and results are monitored and shared. Such an approach could improve restoration practices in the future.

Restoring Connectivity and Assisting Migration

A beneficial impact of ecological restoration is improved connectivity between native ecosystem patches that allows species to migrate more freely and evolve in the face of climate change. Some researchers have advocated that certain species will need special assistance to migrate ("assisted migration"; Kramer & Havens 2009; Sáenz-Romero et al. 2016; Wang et al. 2019). Indeed, many of the provenancing strategies discussed here could be considered a form of assisted migration at the population level. However, when and where this might be warranted is subject to intense debate and comes with risks (e.g. hybridization with closely related species; species become invasive in the new environment). Augmenting species at the edges of their ranges, which may seem logical in many cases, may also be problematic as species are rare along the edges of their ranges for ecological reasons that may be poorly understood. Additionally, populations along range edges are sometimes genetically distinct. Introducing germplasm from other populations could reduce climate readiness or lead to the extinction of the local population through hybridization. Often, range edges are very ragged with many outliers, a condition not well illustrated by many distribution maps (e.g. maps using presence/absence by local political units). The question of when to pull species "up latitude and up slope" along those edges or continue to support populations at low latitudes and at the low-elevation edges of their ranges is complex and deserving of careful thought. Trailing edges of a distribution relative to climate change are most vulnerable to loss of a species. Longevity, dispersal, breeding system, and other species traits determine the ability to adapt or migrate. When sourcing, it is important to consider material from currently adapted sources plus sources adapted to projected near-future conditions to hopefully balance the benefits of local adaptation with the ability to adapt to changing conditions.

Appendix 2

Blank project evaluation templates (for practitioner use)



Ecological recovery wheel

EVALUATION OF ECOSYSTEM RECOVERY

Site_____

Assessor_____

Date_____

ATTRIBUTE CATEGORY	RECOVERY LEVEL (1-5)	EVIDENCE FOR RECOVERY LEVEL
ATTRIBUTE 1. Absence of threats		
Over-utilization		
Invasive species		
Contamination		
ATTRIBUTE 2. Physical conditions		
Substrate physical		
Substrate chemical		
Water chemo-physical		
ATTRIBUTE 3. Species composition		
Desirable plants		
Desirable animals		
No undesirable species		
ATTRIBUTE 4. Structural diversity		
All strata present		
All trophic levels		
Spatial mosaic		
ATTRIBUTE 5. Ecosystem function		
Productivity, cycling		
Habitat & interactions		
Resilience, recruitment		
ATTRIBUTE 6. External exchanges		
Landscape flows		
Gene flows		
Habitat links		

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