Title: Enhancing Biodiversity and Ecosystem Services in Quarry Restoration – Challenges, Strategies and Practice

Running head: Biodiversity and Ecosystem Services in Quarries

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Abstract:

Although covering less than 1% of the land surface, extraction activities have long-lasting impacts on local ecosystems, inevitably damaging biological diversity and depleting ecosystem services. Many extractive companies are now aware of their impacts and, while pressured by society, demand concrete solutions from researchers to reverse the effects of exploitation and restore biodiversity and ecosystems services. In this paper, we compile and synthesize the contributes of the latest available research on quarry restoration. We depict and discuss some of the most pressing issues regarding (1) the challenges of restoring quarries, (2) the opportunities for biodiversity and ecosystem services delivery, and (3) outline further research addressing current gaps. We conclude that quarries pose different abiotic and biotic constraints that act interdependently, hampering the attainment of effective restoration if considered solely. Such constraints need to be addressed holistically to lastly encourage the self-sustainability of the system by reinstating ecological processes. However, a restored site does not have to specifically mimic the pristine situation, as under certain conditions alternative approaches may uphold valuable natural assets contributing to the conservation of rare, restricted or protected species and habitats.

Key words: Ecosystem restoration; Non-energy extractive industry; Spontaneous succession; Assisted restoration; Management practices; Nature-based solutions; Nature conservation

Implications for Practice:

1) All is connected: soil and landform directly affect productivity and environmental conditions, which will determine vegetation and animal communities able to colonize and thrive in these human-made systems.
2) Fully functional and self-sustainable ecosystems are usually the aim of active restoration but less advanced stages may also be of restoration interest.
3) Alternative approaches, such as spontaneous succession, may provide a valuable contribution to nature conservation and ecosystem services, while avoiding expensive restoration or reclamation practices.
4) Quarrying activity should not prevail over conservation of threatened ecosystems, especially if the post-restoration state cannot compensate for the lost natural assets.

Introduction

Increasing demand for natural resources has been fueling the growth rates of resource extraction contributing significantly to biodiversity loss (IRP, 2019). Despite the several global agreements (UN, Aichi Targets), biodiversity continues to change globally (Butchart et al. 2010; Dornelas et al. 2014; Tittensor et al. 2014), with ongoing species loss and/or changes in communities (e.g., species turnover, homogenization). Our knowledge is still too limited to understand the exact consequences of these changes for human's wellbeing and ecosystems resilience, presently and in the future (Branquinho et al., 2019). In response, the United Nations advocated on March 1st, 2019, the 2021 – 2030 period as the "Decade on Ecosystem Restoration" (UNEA, 2019). Though valuable it may be, it leaves us a worrying sign: is no longer enough to protect, we must also restore!

The non-energy mineral extraction sector, for instance, has grown 2.7% and 8.3% per year since 1970 for metals and non-metallic minerals, respectively (IRP, 2019). Although covering less than 1% of the land surface (Walker, 1999), this sector has critical and long-lasting impacts on local ecosystems. Extraction activities inevitably damage ecosystems resulting in biodiversity loss or change and on the depletion of ecosystem services. Restoration (either spontaneous or assisted) stands as a solution to reverse mining and quarrying impacts, thus contributing to improving the environment and, ultimately, human health (Palmer et al., 2010). However, restoration ecology has not yet reached adulthood as an academic field (Young et al., 2005; Roberts et al., 2009). Although mining and quarry restoration have been targeted in many studies (e.g., Prach and Tolvanen, 2016, and references therein), it still struggles with naïve efforts that may hamper the attainment of effective restoration actions (Cooke et al., 2019). In the brink of the Decade on Ecosystem Restoration, researchers and practitioners must engage with industrial stakeholders to commit with meaningful restoration targets built upon empirical and evidence-based research. This will be vital to define priorities to allocate limited and precious resources into effective and successful restoration actions (Cooke et al., 2019).

This was the motto of the Quarries Alive conference held in May 2018 in Évora, Portugal. The aim was to harmonize the current demand for concrete and realistic solutions to restore biodiversity and ecosystems services in the extractive industry. The concept emerged from a consortium between industrial (SECIL, Companhia Geral de Cal e Cimento, S.A.), and scientific stakeholders (University of Évora and the Faculty of Sciences of the University of Lisbon). The conference involved about 150 participants (from 21 countries) representing different stakeholders including restoration ecologists, industrial managers and technicians, NGO's and policymakers. Most contributions to this special issue were presented at the conference, which accounted for 34 oral presentations and over 20 posters.

The collection of papers here presented depict some of the most pressing issues regarding mine and quarry restoration. We assembled contributions focused on the non-energy extractive sector, which include: sand or gravel pits, open-cast quarries of several mineral materials (clay, granite, gypsum, limestone, and others), either active or inactive, while extending it to mine by-product structures such as steep slopes, stockpiles, or spoil heaps. In this paper, we describe and incorporate the main considerations and implications of these studies. We synthesize this information into three major topics:

- Challenges of restoring quarries: we highlight emerging techniques and approaches to restore quarries in the face of demanding conditions imposed by landform constraints and increased environmental degradation;

- Quarries as opportunities for biodiversity and ecosystem services delivery: open-minded approaches that look for alternative solutions while taking advantage of novel conditions to promote biodiversity and ecosystem services;
- Further gaps in the restoration of extractive sites: an overview of issues yet to be addressed or requiring further consideration in future approaches for mining and quarry restoration.

The challenges of restoring quarries

It comes as no surprise that mining and quarrying significantly alter local geomorphology, soil, vegetation and fauna. The exploration is traditionally considered to result in a much-degraded site that challenges restoration practitioners to overcome barriers involving unstable substrates, rocky steep slopes, nutrient-poor, acidic or alkaline soils, and a depleted biotic component that extents to collapsed ecosystem services.

Whisenant (1999) in his conceptual model (see also Hobbs and Harris, 2001) identifies a first barrier controlled by abiotic limitations (see Fig. 1 for an adaptation of Whisenant's model to mine and quarry restoration). At this stage, restoring soil properties and landforms are necessary to reinstate soil functions, thus preventing from erosion, water drainage or retention, and nutrient leaching, which ultimately will determine vegetation settlement.

As an example, Lane et al. (this issue) and collaborators found that mesotrophic grasses dominated former kaolinite mining sites, instead of typical lowland heath species. Such differences in vegetation composition were attributed to soil characteristics, which revealed lower acidity levels and organic content. This evidence was obtained for both short (2 years) and long-term (150 years) restored sites, and even when stockpiled overburden was reinstated. Key nutrients and pH were, therefore, affecting soil fertility and potentiating different vegetation communities at restored sites, leading restoration programs to undershoot their targets. The authors concluded that soil was the limiting factor and, in order to prevent its shortcomings, multiple interventions were advanced to secure soil fertility, such as reducing storage time and depth of overburden and admix organic material to preserve soil mesofauna and microbial properties.

Carabassa et al. (this issue) further extended this issue by evaluating the effects of manufactured soils (Technosols) on carbon sequestration and vegetation development. Organic soil amendments, provided by properly treated sewage sludge, revealed to outperform soils without amendments, an effect that echoed until the ten years of experiment. Indeed, Technosols contributed greatly to the development of vegetation and community complexity, speeding up the natural succession processes without altering significantly vegetation composition. As a result, the amount of soil organic carbon sequestered was three times higher due to an increase of primary production supplied by the rich-nutrient content of sludge organic matter.

Besides vegetation, overlooking soil properties can have cascading effects on animal communities. Eufrázio et al. (this issue) measured the effects of quarry exploitation and restoration on population dynamics, individual movement, and habitat use of a sand-dwelling beetle (*Scarites cyclops*). While thriving in surrounding areas not subjected to intervention, the beetle showed lower abundance and limited dispersal ability in the restored area. Further investigation places responsibility on inorganic soil amendments and fertilization that altered soil texture from typical fine sand soils (grain size < 4 mm) to gravel (size > 2 mm). In addition, soil amendments readily promoted an abundant and displaced herbaceous cover, which hampered the ability of the species to move and dig for shelter.

The interdependent relation between substrate, animal communities and vegetation was also explored by Mexia et al. (this issue) using a multitaxa approach. While looking for differences between restored and reference sites, they found that both the composition and structure of the epigean beetle community was greatly altered, despite restoration practices efficiently promote a rapid recovery of vegetation cover. Habitat modifications stemming from conifer plantations used to reclaim impacted sites provided further changes on native vegetation while possibly affecting substrate from litter accumulation and concealing natural rock outcrops. Differences on trophic guilds between restored and reference sites could be thus attributable to a different availability of ground food resources.

The relation between the abiotic and biotic components is rather complex, and even more challenging when soil is lacking. Steep slopes present highly adverse edaphic conditions and enhanced surface runoff. In the face of these limitations, vegetation seldom establishes in such sites, and slopes are frequently left exposed and unmanaged. An innovative technique that has been proposed consists of vertical greening systems, or Green Walls (Medl et al., 2017). Monteiro et al. (this issue) studied the effectiveness of green walls in steep slopes under different conditions, by assessing vegetation establishment and spontaneous colonization. Their results validate the use of geotextiles to retain the substrate. Even under different environmental constraints, the vegetation evolved similarly, benefiting spontaneous colonization by native species, more adapted to local conditions. Monteiro et al. (this issue) further explored the compositional and functional diversity of vegetation community and found that alleviating limiting conditions (e.g. using irrigation) would only increase functional redundancy. They argue that low-intensity intervention was enough to ensure ecosystem services, moreover being more cost-effective.

Another transition threshold is, thus, introduced by a biotic barrier (see Fig. 1). Ecosystem functioning relies on the interplay within and between the biotic and abiotic components of an ecosystem, i.e., ecological processes. Reinstating ecological processes will allow the system to regulate itself without the need for active intervention. With this in mind, Salgueiro V. et al. (this issue) investigated how carnivore mammals could assist spontaneous restoration, while comparing emergence and survival of seeds dispersed by carnivores into a quarry. The authors concluded that, although endozoochorous seedlings showed greater mortality rates, still a high amount of viable seeds survived, contributing to complement restoration efforts. As long as restored areas remain accessible and attractive, species inhabiting the vicinity of quarries can enable seed dispersal during their incursions, thus encouraging the self-sustainability of the system.

Quarries as opportunities for biodiversity and ecosystem services delivery

Although mines and quarries are often regarded as biodiversity sinks, a great deal of research up-rises with renewed perspectives claiming valuable natural assets potentiated by post-mining or -quarrying conditions (e.g., Řehounková et al. 2016). Calvo-Robledo et al. (this issue), for instance, concluded in their study that setting restoration targets that also account for nature conservation may promote ecosystem services in a socio-economic perspective. While using a participatory approach they were able to demonstrate potential ecosystem services provided by restoration scenarios of an active quarry, weighted by cultural (nature-based recreation), regulating (greenhouse gas emission and sequestration), and provisioning services (agricultural production). The associated costs and annual income could be optimized if nature-based solutions are taken into account while planning the post-quarry end-use.

Informed decisions, however, often require evidence-based approaches that can advise on alternative solutions to restore and value biodiversity. Some studies figuring this special issue provide approaches that detach from prevailing technical reclamation techniques generally oriented to minimize visual impacts, improve safety protection of the mining infrastructure, or further profit from the forest or crop harvest.

For example, Šebelíková et al. (this issue) found that spontaneously revegetated post-mining sand and sand-gravel pits hosted more dry and mesic grassland species considered rare (or threatened) and specialists of open sand habitats in early than late successional stages. Although a large overlap in species composition was detected between spontaneously revegetated and reclaimed sites, most of the conservation interest of the later was lost after a few years following artificial afforestation. The authors suggest that spontaneous revegetation should be considered in post-mining areas, as long as nearby (semi-)natural habitats can source vegetation propagules into mined sites. Řehounková et al. (this issue) support this approach as well. In their study, they assessed vegetation communities of 321 post-mining sites at different successional stages. They identified 235 threatened plant species overall, concluding that post-mining sites act as important refugia for the species. Moreover, early successional habitats offer the most important conditions for threatened plants, which gradually degrade with increasing woody species cover.

Not only plants, but also animal species may thrive in such degraded habitats. Rohrer et al., Salgueiro P. et al. and Martin-Collado et al. (all in this issue) studied the habitat preferences of two cliff-nesting bird species – the Sand Martin (*Riparia riparia*) and the Black Redstart (*Phoenicurus ochruros*) – and a semiaquatic mammal – the

Eurasian otter (*Lutra lutra*). In the first two studies, both authors found that the species were attracted to mined areas especially when unsuitable conditions prevailed in surrounding matrix habitats. Sand Martins, for example, benefited from sand stockpiles of extracted material or sandy faces of gravel pits, which were used to burrow their nests. Black Redstart, on the other hand, occurred in limestone exposed slopes that mimic natural steep cliffs of rocky habitats, where it naturally occurs. Regarding the Eurasian otter, the authors found that gravel pit lagoons could provide suitable habitats for semiaquatic species in anthropogenic landscapes, if restoration attends to certain environmental features. These studies discuss the possibility of creating or enhancing habitat by allowing for the preservation of novel elements in the landscape potentiated by mining and quarrying activities. Such practices may also apply in the course of mining operations, providing temporary habitats. This approach, despite feasible, still raises some debate. One of the most relevant questions regards the promotion of habitats surrounded by low-quality areas, which in the event of not providing enough resources may create an ecological trap, such as discussed by Rohrer and co-workers.

Řehounková et al. (this issue) refer in their study that post-mining sites, especially if left to spontaneous restoration, can operate as secondary or surrogate habitats for species of conservation concern. The approaches presented here can be alternatives to inadequate restoration practices (Perring et al. 2013), and can contribute to maximize local biodiversity (Doley & Audet 2013). However, all authors stress that these alternatives are conditional and site-dependent, and may only happen ‘under certain conditions’. In fact, these alternatives and opportunities may hinder or conflict with some reclamation approaches.

Further gaps in mining and quarry restoration deserving attention

Mining and quarrying sites are increasingly attracting the attention of ecologists, and though restoration processes are being intensively debated, much knowledge is still lacking. We highlight three major issues that deserve a future commitment from researchers, practitioners and other stakeholders:

1) Measuring the Net Impact of restoration (the gains and losses) has been a major liability of most projects. Many of them have limited insight on ecosystem attributes that can produce objective measures of restoration success, mostly relying on vegetation structure, diversity, or indirect measures of ecological processes (Ruiz-Jaen and Aide, 2005). Part of the problem relies on the dimensionality of the biodiversity concept, which hampers the attainment of objective measures that integrate all dimensions (Nakamura et al. 2019). Mining and quarry restoration share the same problem alike. Furthermore, many extractive companies already acknowledge their impacts on ecosystems and biodiversity (assisted by increasing awareness and pressure from society), and demand concrete solutions from researchers to disclose their efforts in restoring degraded sites. Under these circumstances, developing holistic approaches showing the relation between both biotic and abiotic components and how they intertwine into ecological processes and socio-economic circumstances is crucial to address the Net Impacts of extractive industry. In this matter, cost-benefit analysis may assist weighing the Net Impact of exploitation.
2) Several studies in this issue showed that preserving or enhancing unique characteristics of quarries can sustain threatened and other conservation interest species or communities, if properly managed. However, broader scales should also be considered. Throughout Europe many habitats of conservation concern faced recent declines (e.g., calcareous grasslands, Wallis de Vries et al. 2002,

Ödman and Olsson, 2014) or are currently receding, causing important declines in species, communities and ecological processes associated with them. If mining or quarrying areas hold the potential to sustain such habitats, they can complement existing protected habitats when oriented by suitable restoration practices. The establishment of a strategic network connecting these areas as stepping-stones should enable species to move across the landscape (Saura et al. 2014). Such an approach is considered within the Green Infrastructure concept. The adoption of a Green Infrastructure Agenda can uphold the importance of former mining or quarrying sites as reservoirs of specific ecosystems. Therefore, spatial and temporal approaches at broader scales are necessary to design those networks and set targets that guide restoration practices into wide-ranging contexts.

3) Finally, as many studies preview in this issue, restoring mine sites or quarries are among the most challenging tasks, given their starting point. In a climate change scenario, the expected changes are likely to have overarching effects on restored sites, mainly upon the soil, water availability and vegetation establishment, and on the processes they are involved in. Many approaches are now available that can simulate future climate change scenarios at micro- and meso-scales (see Maestre et al., 2013, Léon-Sánchez et al. 2017). Such approaches are of interest for companies involved in restoration activities willing to adapt their practices to future climate forecasts, thus improving habitat resilience.

Concluding remarks

As the demand for mineral extraction grows, restoring mines and quarries emerges as a relevant issue to respond to both stakeholders and general society concerns. Researchers and practitioners are being challenged to provide informed and efficient solutions to respond to both ecological and economical demands.

This special issue on “Enhancing Biodiversity and Ecosystem Services in Quarry Restoration – Challenges, Strategies and Practice” resumes several topics that address the best guidance practices to restore such degraded sites. A few key practices reported are as follows:

1) First interventions usually focuses on landform and soil fertility. Storage of stockpiles, soil amendments, and landform will have direct impacts on soil quality and edaphic conditions, which in turn will determine soil biota, vegetation and animal communities able to colonize and thrive in these systems. Furthermore, the soil will also provide some ecosystem services.
2) However, there are also more and more evidence that low-fertility sites with rough substrates can be profitable for some rare and retreating specialists, both plants and animals. Thus, restoration measures that will strongly change site environmental conditions should be carefully considered before any decision is made.
3) Analyses of community composition and structure allow the assessment of effectiveness of the restoration practices. Using local native species while taking advantage of (semi-)natural conditions on the vicinity can unequivocally improve restoration success.
4) Assessing how communities are performing their functions will further contribute to understanding if ecological processes are being upgraded.

Only a fully functional system can be self-sustainable, and will further allow for species to play their part in assisting restoration.

5) Under certain conditions, alternative approaches, namely those relying on nature-based solutions (e.g., spontaneous or only slightly assisted restoration), may uphold valuable natural assets in post-mining or -quarrying sites, avoiding expensive (and sometimes inadequate) classical restoration or reclamation practices, and further upholding ecosystem services.
6) Nonetheless, mining or quarrying activity should not prevail over threatened ecosystems or of conservation concern, especially when the conditions created afterwards through restoration cannot match the lost natural assets.

Acknowledgements:

The publication of this special issue would not have been possible without the sponsorship of SECIL — Companhia Geral de Cal e Cimento, SA. We are most thankful to Michael Rademacher for his early contribution on the making of this special issue. We would also like to accredit Carmo Silva and Alexandra Silva, on behalf of the organizing committee of the Quarries Alive 2018 conference, for their support and endorsement in complying with this goal. KP acknowledges the support from the project no. 20-06065S granted by the Czech Grant Agency. The authors declare that there is no conflict of interest.

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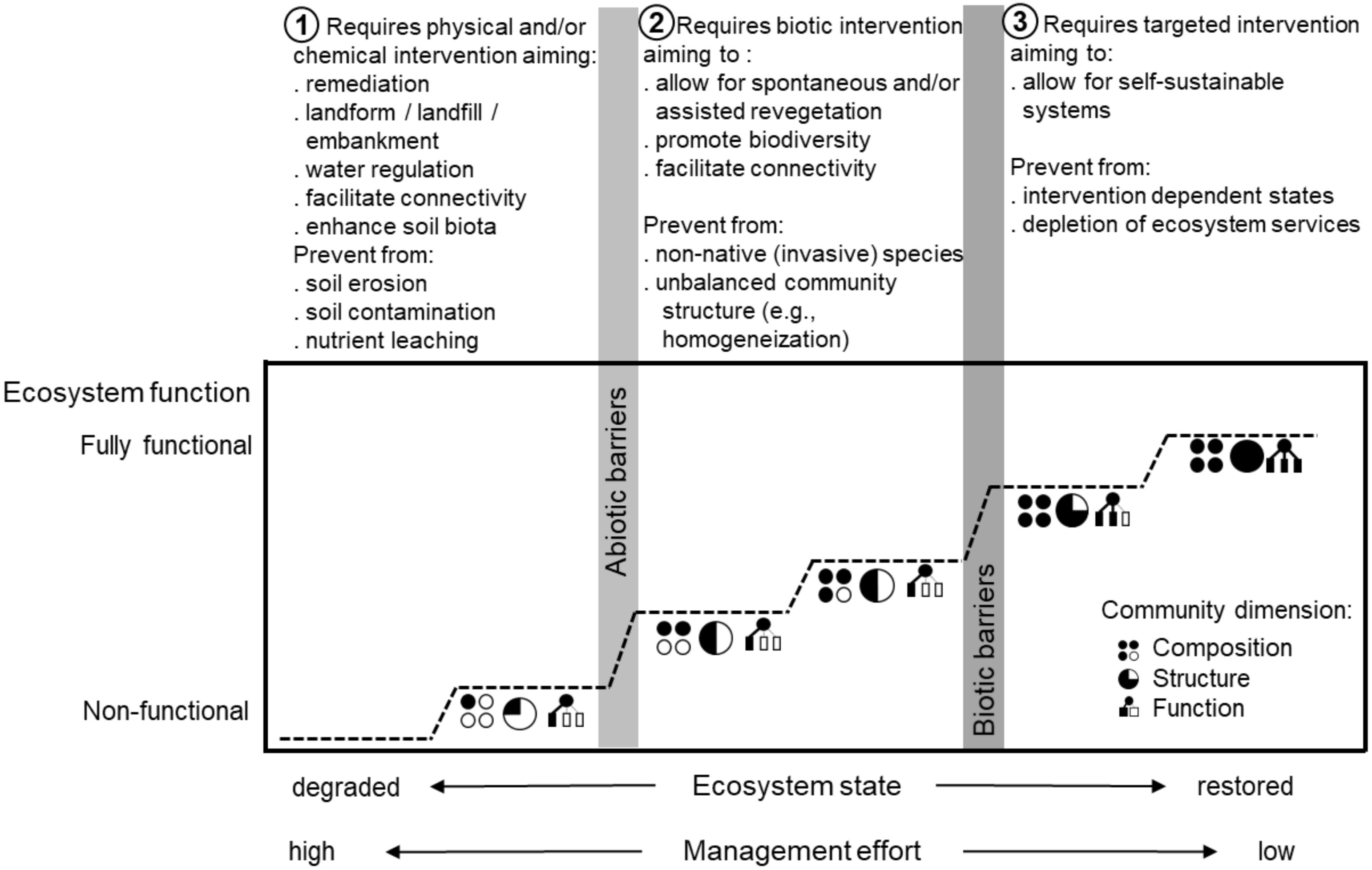
Figure caption

Figure 1 – Classical conceptual model of state transition along a degraded to restored gradient targeting mining and quarry restoration (adapted from Whisenant 1999, Hobbs and Harris, 2001). Horizontal dashed line signals the different hypothetical equilibrium states along the gradient; diagonal dashed line signals transition between states. Each state transits to a more or less functional system (with increasing complexity of the community dimensions) according to the interventions that promote either restoration or degradation, respectively. Interventions can be grouped at three levels, according to their aim and extent: (1) physical and/or chemical when the site requires landform or soil preparation to assist revegetation, (2) revegetation to encourage the settlement of communities attending to both composition and structure, either spontaneously or actively intervening, and (3) targeted or focal, in order to allow for naturally assisted restoration through reinstating ecological processes. Between each level, abiotic (between level 1 and 2) or biotic (between level 2 and 3) barriers exist, marking thresholds which need to be overcome to assist subsequent interventions. The intensity of these thresholds may vary between site condition and overall restoration target. Overcoming these barriers can be either promoted by spontaneous (supported by ecological succession when barriers can be naturally overcome) or active intervention (if barriers are naturally constrained). In this conceptualization, a restored site does not have to specifically mimic the pristine situation, but to be fully functional, i.e., hold self-sustainable communities at long-term while requiring minimal or no intervention.

Figure 1


① Requires physical and/or chemical intervention aiming:
. remediation
. landform / landfill / embankment
. water regulation
. facilitate connectivity
. enhance soil biota
Prevent from:
. soil erosion
. soil contamination
. nutrient leaching
② Requires biotic intervention aiming to :
. allow for spontaneous and/or assisted revegetation
. promote biodiversity
. facilitate connectivity
Prevent from:
. non-native (invasive) species
. unbalanced community structure (e.g., homogeneization)
③ Requires targeted intervention aiming to:
. allow for self-sustainable systems
Prevent from:
. intervention dependent states
. depletion of ecosystem services
Ecosystem function
Fully functional
Non-functional
Abiotic barriers
Biotic barriers
Community dimension:
Composition
Structure
Function
degraded
Ecosystem state
restored
high
Management effort
low