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Grand challenges in ecosystem restoration

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Introduction

Humanity has now breached six of the nine 'planetary boundaries' that define the safe operating space in which our civilization evolved (Richardson et al., 2023). As natural systems come under increasing anthropogenic pressure, it is imperative that we safeguard our ecosystems and the services they provide. Such efforts must extend beyond protection of the habitat that remains, and embrace the global restoration of areas that have been degraded through land use conversion, pollution, and over-exploitation. Governments worldwide have recognised the urgency of this mission, launching the 'UN Decade on Ecosystem Restoration' in 2021, and committing to large-scale restoration efforts through the Bonn Challenge, The Glasgow Leaders' Declaration on Forests and Land Use, the Kunming-Montreal Global Biodiversity Framework, and more. Yet restoration efforts on the ground have lagged far behind targets set by these and pre-existing global initiatives. For example, the 2010 Aichi Biodiversity Target of restoring 15 percent of degraded ecosystems was not achieved by 2020 (Convention on Biological Diversity, 2020), and 10 million hectares of forest continued to be lost each year between 2015 and 2020 (FAO and UNEP, 2020). To accelerate ecosystem restoration and meet policy targets, two key obstacles must be overcome. The first challenge is to implement restoration innovations at the scales necessary to halt and even reverse net loss of forest, grassland, wetland, mangroves, and other habitats. The second challenge is to achieve this large-scale restoration in a way that involves the full participation of local stakeholders.

Scaling restoration solutions

The response of any particular site to a standard management intervention will be highly context dependent, which challenges restoration practitioners. Community dynamics in any ecosystem are very sensitive to stochastic processes, including priority effects (when the random order of species arrival influences subsequent community development) (Weidlich et al., 2021), unpredictable disturbances, climatic fluctuations, etc. Although there is an increasing focus on landscape-scale approaches to ecosystem rehabilitation, in practice, restoration interventions are often conducted at relatively small scales, and geared towards solving site-specific problems (Murcia and Aronson, 2014; Perring et al., 2015).

One way to enhance the success of a site-specific intervention is to ground specific restoration practices in a more general theoretical understanding of community ecology. Over the 20th century, advances in restoration technique emerged from the study of community assembly, the process by which species with the capacity to inhabit a particular region (i.e., members of the 'regional species pool') surmount environmental filters to become part of the local species pool (Keddy, 1992). To successfully establish at a site, a particular species must arrive (overcome dispersal limitation), be able to tolerate microenvironmental conditions (pass the abiotic filter), and coexist with the other species resident in the local community (pass the biotic filter) (Kraft et al., 2015). Each of these filters may be targeted by restoration ecologists to influence the composition or diversity of species at a site. For example, practitioners can introduce seed-containing substrate to surmount dispersal limitation (Kiehl et al., 2010), enhance microtopography to maximise variation in the abiotic environment (Török et al., 2018), or modify species interactions through removal of invasives. In this way, ecologists have adopted general theoretical ecological approaches to address site-specific conditions.

Although the field of restoration ecology has rapidly advanced alongside our theoretical understanding of ecological communities, theory-inspired approaches must be upscaled in order to restore habitat at the speed and spatial extent required. This can invoke significant practical and logistical challenges. For example, while transferring litter or soils from a 'donor' to a 'recipient' site can propel ecosystem regeneration (Buckley et al., 2017; Contos et al., 2023), how can these practices be extended to large areas of degraded lands without damaging the donor sites? Can labour-intensive restoration practices–e.g., intentional application of small-scale disturbance, manual removal of invasives - practically be applied at scale? How can restoration outcomes (particularly those related to ecosystem function or resilience) be monitored over large areas? Taking a broader lens on restoration also invokes the need to consider landscape-level ecological processes, assessing connectivity and permeability among habitat classes (Metzger et al., 2021).

Scaling up restoration could involve finding compromises between passive restoration (allowing ecosystems to recover on their own–which is inexpensive, but sometimes ineffective) and active restoration (spending time, money, and effort to directly modify an ecosystem). These intermediate approaches, termed assisted natural regeneration, might involve planting tree 'islands' rather than large-scale plantations in degraded landscapes, a technique sometimes referred to as applied nucleation (Holl et al., 2011; Wilson et al., 2021). Strategic plantings like this can improve landscape connectivity, enhance abundance of animal-dispersed plant species, and accelerate habitat recovery at minimal cost (Holl et al., 2011; De La Peña-Domene et al., 2016; Werden et al., 2022). However, there are still large knowledge gaps surrounding the suitability of individual sites or landscapes for passive vs assisted vs active restoration (Holl and Aide, 2011; Crouzeilles et al., 2017; Reid et al., 2018); we must learn to rapidly 'triage' ecosystems to best allocate time and effort.

Another way to scale restoration is to operationalise our understanding of plant-animal and plant-microbe interactions. Re-introduction of keystone species, especially predators which exert top-down control (i.e., 'trophic rewilding'), might be another way to restore ecosystem integrity with minimal direct intervention (Perino et al., 2019). One study found that re-introduction or re-colonization by only twenty species could dramatically increase the intactness of large mammal assemblages worldwide (Vynne et al., 2022), but research on the ecological consequences of such re-introductions is far from complete. Conversely, restoration efforts might employ 'bottom-up' approaches that focus on the soil microbes which release and transport plant-available nutrients, secrete growth-promoting hormones, and mediate plant community succession through plant-soil feedbacks. Until recently, most restoration efforts failed to consider whether and how to re-introduce beneficial microbes to a site–and without intervention, recovery of the soil microbiome in revegetated sites is often incomplete (Watson et al., 2022). Although inoculation with specific, beneficial plant symbionts (i.e., mycorrhizal fungi) is a relatively well-established practice (Neuenkamp et al., 2019); more recent work explores the possibility of plant inoculation with whole-soil or phyllosphere microbiomes to accelerate ecosystem recovery (Wubs et al., 2016; Busby et al., 2022). At the frontier of this science are efforts to actually re-engineer microbial communities to re-establish specific ecosystem processes (Silverstein et al., 2023)–this is a promising approach that is nonetheless still in its infancy.

Tackling the challenge of upscaling restoration will involve technological advances, as well as theoretical and operational ones. Such developments might include the invention of new equipment/infrastructure to help native species to spread and re-establish (Temmink et al., 2020); the deployment of sensors and satellites for monitoring restoration projects at scale; and the data infrastructure necessary to share, analyse, and synthesise information about restoration outcomes (Perring et al., 2015). Much of this technology is still in the early stages of its development. Yet there is an urgent knowledge gap surrounding the effectiveness of restoration projects, which can only be addressed by fusing large-scale monitoring and local, site-specific expertise. For example, although just 5% of tropical reforestation organisations monitor survival rates of the trees they plant (Martin et al., 2021), emerging syntheses suggest that these projects exhibit relatively high rates of failure (Coleman et al., 2021), with mortality rates approaching 50% in the first few years (Banin et al., 2023). Yet it is very challenging to understand the factors that limit project success, as many landscape restoration efforts do not solicit sufficient involvement of local stakeholders in planning, data collection or monitoring (Evans et al., 2023).

Finally, large-scale rehabilitation of degraded lands will also involve careful attention to the socioeconomic factors that drive land use change–which itself comprises another major challenge to twenty-first century restoration.

Integrating restoration into socio-ecological systems

Many restoration efforts fail because they do not consider the needs and motivations of local stakeholders who interact most directly with the land (Brancalion and Holl, 2020; Fleischman et al., 2020). Just as restoration practitioners must grapple with the heterogeneous ecological processes that affect ecosystem regeneration, so must they confront the diverse social, political, and economic contexts in which restoration takes place. There is an urgent need to better understand the enabling conditions that promote successful restoration, and how these conditions might vary from place to place.

Ecosystems can spontaneously recover in agricultural landscapes where pressure on land use conversion is low, usually due to population migration out of rural areas and into cities, and/or changing agricultural policies (Chazdon et al., 2020; Crouzeilles et al., 2021). It is more difficult to incentivise restoration in areas where there is a high opportunity cost of forgoing land use conversion, or of abandoning land already in production. To ensure restored habitat persists on the landscape, landholders must be compensated for these costs. However, devising appropriate payment for ecosystem service schemes can be complicated. Any uncertainties in land tenure or land access rights can dramatically weaken incentives for restoration, or displace land degradation into other areas (Ford et al., 2020). For example, in some jurisdictions, ceasing agricultural land use terminates a landholder's rights to that land, and 'idle' (naturally regenerating) habitat can invite land grabs (Holl et al., 2022). Additionally, although indigenous peoples are frequently the best custodians of intact ecosystems, their rights to land are often opposed by regional or national governments (FAO, 2021; Kruid et al., 2021; Haenssgen et al., 2022). It is very challenging to map interactions among local, regional, and (inter-)national governance structures that impact land use, but such a holistic understanding must be achieved to effectively restore ecosystems with the full participation of the people who depend on them.

In order for restoration to be successful, projects must be co-designed with the people with the most to gain (or lose) from their implementation (Waring et al., 2023). This can happen through 'top-down' approaches, where a centralized, decision-making body (e.g., national government) leads restoration efforts, in consultation with diverse stakeholders; or 'bottom-up' processes where local communities initiate the behavioural change (Reed et al., 2018). Each approach has pros and cons. For example, the Chinese government initiated the 'Grain-for-Green' programme, the world's largest reforestation effort to date. In an attempt to control soil erosion, landholders were paid to plant trees on scrubland (Hua et al., 2016). Although this effort had a dramatic impact on forest cover in China, much of the planted forest consists of monocultures that are depauperate in biodiversity (Hua et al., 2016), and in some areas these forests lost more water to the atmosphere than native grasslands, contributing to regional water shortages (Schwärzel et al., 2020). In this example, a top-down restoration approach achieved speed and scale, but potentially at the cost of environmental integrity. By contrast, a 'bottom-up' approach is exemplified by the 'regreening' that took place in the Sahel region from the 1980s onward. By building upon traditional knowledge, smallholder farmers were able to encourage the natural regrowth of trees on their lands, reducing desertification and improving food security for an estimated three million people (Magrath, 2020). High-resolution satellite imagery now shows that 1.8 billion trees are growing in a region typically thought of as the exemplar of dryland desertification (Brandt et al., 2020). It is important to note, however, that the restored lands are still under active agricultural management. This groundswell movement did not intend - nor did it achieve - the full restoration of native, unmanaged habitat. Enhancing biodiversity and carbon sequestration in agricultural landscapes is crucial, but some portion of the landscape must be fully restored to halt the precipitous decline in biodiversity.

Over the last 2 decades, the 'Forest Landscape Restoration' (FLR) approach has emerged to consider how habitat protection and restoration can be balanced with agriculture and forestry at the landscape scale (César et al., 2021). Integral to this approach is participatory planning–collaboration among governments, NGOs, landowners, and local communities is vital to assess how multiple ecosystem services can be maximised simultaneously (Aguiar et al., 2021). This can open up new frontiers for ecosystem regeneration: millions of hectares could be restored in landscapes currently dominated by smallholder agriculture, if the right institutional supports and market conditions are put in place (Busch et al., 2019; Shyamsundar et al., 2022). As the FLR approach is a relatively recent development, we urgently need more information about when and where such interventions are successful, and how restored landscapes can be adaptively managed over time in the face of continuously changing socioeconomic conditions.

Conclusion

There are no universal solutions in restoration ecology. Each site reflects the unique confluence of environmental, ecological, sociological, and historical factors that shape its present-day function. Ignoring any of these context dependencies can lead to restoration failure–yet to preserve biodiversity and safeguard ecosystem services, large areas of degraded land must be restored very quickly. To achieve cost-effective large-scale restoration without the pitfalls of 'one-size-fits all,' site-agnostic management protocols, practitioners should seek to harness natural regeneration processes wherever possible. We must also acknowledge that no restored landscape can persist without the participation of local stakeholders. Although there are many viable pathways to connect these stakeholders with regional, national, or global-scale finance streams and governance frameworks, all must involve a bidirectional exchange of information, ideas, and resources. Twenty-first century restoration will require much more collaboration across disciplines, from economics to anthropology to engineering; as well as among academics, policymakers, landowners, and conservation practitioners. These tasks pose an enormous intellectual and practical challenge–but it is one we must surmount to leave a functional biosphere for future generations.

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BW: Conceptualization, Writing–original draft.

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