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Editorial

Supporting the restoration of complex ecosystems requires long-term and multi-scale perspectives

Sophie Monsarrat, Néstor Fernández, Henrique M. Pereira and Jens-Christian Svenning

S. Monsarrat (https://orcid.org/0000-0002-6220-5306) ✉ (sophiemonsarrat@gmail.com) and J.-C. Svenning (https://orcid.org/0000-0002-3415-0862), Center for Biodiversity Dynamics in a Changing World (BIOCHANGE), Dept of Biology, Aarhus Univ., Aarhus C, Denmark and Section for Ecoinformatics and Biodiversity, Dept of Biology, Aarhus Univ., Aarhus C, Denmark. – N. Fernández (https://orcid.org/0000-0002-9645-8571) and H. M. Pereira (https://orcid.org/0000-0003-1043-1675), German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig, Germany and Inst. of Biology, Martin Luther Univ. Halle-Wittenberg, Halle (Saale), Germany. HMP also at: CIBIO (Research Centre in Biodiversity and Genetic Resources)–InBIO (Research Network in Biodiversity and Evolutionary Biology), Univ. do Porto, Vairão, Portugal.

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The United Nations General Assembly has declared 2021–2030 the Decade on Ecosystem Restoration, during which the recovery of degraded nature should be massively upscaled to effectively fight the climate and biodiversity crises (<www.decadeon-restoration.org/>). Furthermore, the Parties of the Conference on Biological Diversity confront the challenge of setting ambitious targets to not only protect species and ecosystems, but also to revert degradation trends and restore functional nature. This requires a significant increase in the area, connectivity and integrity of natural ecosystems (Convention on Biological Diversity 2021). Global policy thus put restoration of degraded ecosystems at the forefront of the range of actions that should be promoted to address the twin crises of climate change and biodiversity loss.

The scientific community plays a key role in building the knowledge base necessary to support the global restoration agenda and to help point towards effective solutions for society (Gann et al. 2019). In a recently published synthesis on the science underpinning the post-2020 Global Biodiversity Framework (GBF), 50 scientists from 23 countries challenged the GBF focus on area-based targets for conservation and restoration, noting that too much emphasis on protected areas may fall short of meeting ambitious biodiversity objectives (Leadley et al. 2022). This is in line with the idea that conserving remnants of nature in protected areas and protecting endangered species are no longer sufficient to bend the curve of biodiversity loss (Leclère et al. 2020). Restoration efforts should shift towards proactive, functionalist, approaches to nature management, guided by evidence and knowledge of socioecological dynamics at various scales.

Scientific research in spatial ecology, macroecology, biogeography and at their intersections with society and policy are particularly relevant to support decision making and to upscale restoration efforts. This Ecography special issue presents a set of empirical and theoretical articles that together offer a critical analysis of next directions for the field of restoration science at multiple geographical scales. The studies cover three main topics: 1) complexity as a key objective for restoration; 2) the assessment of restoration

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effectiveness, including careful consideration of baselines; 3) potential and challenges for upscaling restoration.

Complexity as a key objective for restoration

Bullock et al. (2021) question the dominant paradigm of ecological restoration for primarily focusing on re-creating the community composition of 'indigenous' reference systems and for prioritizing community composition over ecological processes. They suggest a shift towards achieving or increasing ecological complexity – defined as 'the number of components in a system and the number of connections among them' (e.g. species, trophic structure, connectivity) – at multiple spatial scales. In this framework, the focus of restoration is on enhancing emergent properties, such as the range and level of ecological functions supported by the system and its resilience (i.e. the ability of a system to resist or recover rapidly from a perturbation).

The prediction that higher ecological complexity is linked to enhanced emergent properties such as ecosystem function and resilience finds support in two studies using theoretical approaches (Storch et al. 2021) and trophic network modelling (Mittelman et al. 2021). Storch et al. (2021) use the theoretical framework of the equilibrium theory of biodiversity dynamics (ETBD) to demonstrate that relatively high equilibrium biodiversity levels can be achieved by nurturing the resource fluxes necessary for the maintenance of stable total community abundance and biomass production. Community biomass and diversity can also be enhanced by ensuring the presence of trophic interactions that control dominant competitors as well as the presence of ecosystem engineers. In a modelling study on ecological networks in an Atlantic Forest site in Brazil, Mittelman et al. (2021) demonstrate the importance of restoring trophic network complexity. They show that restoring three frugivore keystone species has disproportionate impacts on the structure and properties of trophic networks, with an increase in network connectance, nestedness, robustness and number of pathways that is greater than the sum of isolated effects for each species.

This is well aligned with the general framework for rewilding proposed by Perino et al. (2019), which argues for restoration along trophic complexity, dispersal/connectivity and stochastic ecosystem disturbances, and the interactions between these ecological processes. In particular, this points towards the importance of recovering keystone species that promote the trophic complexity (in line with the trophic rewilding concept defined in Svenning et al. 2016), the functional integrity and the ecological resilience of ecosystems, similarly highlighted in Bullock et al. (2021). Rewilding can thus be seen sitting with a broader framework of restoration aiming at restoring ecologically complex ecosystems to promote functional integrity and resilience and higher landscape-scale biodiversity (Fernández et al. 2017, Perino et al. 2019, Svenning 2020, Carver et al. 2021).

Assessing restoration effectiveness, including careful consideration of baselines

Assessing the progress of restoration efforts is vital to use resources effectively and to document the effectiveness of different management approaches. For example, Zhang et al. (2021) illustrate the challenge of restoring mangrove habitats to pre-degraded states after aquaculture abandonment. In a case study in Hainan Island, China, they find that neither passive (without planting) or active (with planting) pond-to-mangrove restoration programs have succeeded in recovering the initial species diversity of mangrove, macrobenthos, fish and waterbird communities present in unaltered sites, more than 20 years after the initiation of restoration efforts. This is in line with theoretical predictions that habitat degradation reduces the total amount of resource available to biota and decreases equilibrium diversity (Storch et al. 2021). It also raises the importance of considering passive rewilding as a cost-effective restoration strategy, as it often performs at least as well as active restoration efforts, although key attention should be made to the risk of hysteresis effects that may limit recovery of ecological complexity (Van Meerbeek et al. 2019).

Focusing on seven European rewilding sites, Segar et al. (2021) quantify changes over time across three central rewilding components that aim to encompass key ecological processes that are essential for self-organizing and complex systems: stochastic disturbances, trophic complexity and dispersal. They then use expert elicitation to measure progress along these components and find overall progress for five of the seven sites, and decrease in the two remaining sites, attributable to an increase in human forcing. Their findings suggest that restoration progress is often limited by external pressures, affecting the ability to upscale restoration efforts outside specific sites. Future interventions should be complemented by legislative changes at a higher level if restoration and rewilding are to become effective across landscapes.

We live in a human-dominated world where restoring ecosystems to fixed reference system may no longer be an attainable, or desirable, target (McNellie et al. 2020). Yet, even as the objective of restoration, and in particular rewilding, is future-oriented, restoration opportunities can be broadened via a long-term perspective, providing a better understanding of biodiversity potential, ecological dynamics and the natural processes that have generated and maintained biodiversity and ecological resilience across thousands to millions of years (Svenning 2020). Looking into the past can be used to position the present in relation to these ecological legacies and inform restoration interventions for the future (Turvey and Saupe 2019).

Monsarrat and Svenning (2021) suggest looking into the deep past to contextualize megafauna restoration in relation to deep-time extinctions and countries capacity to support restoration. They reveal an unfair burden placed on countries from the Global South when modern or historical temporal baselines are used to identify the set of species that are native to an area – and thus candidate for reintroductions. When using a mid-Holocene or Pleistocene baseline, new opportunities arise for megafauna restoration in Europe and North America, respectively, where countries have a higher financial and societal capacity to support megafauna restoration. Consequently, using recent baselines as benchmarks for restoration influences how we assess the success of restoration efforts, with less ambitious targets being placed upon areas where ecological impacts happened a long time ago. There are thus not just important ecological consequences, but also strong political and ethical implications to the choice of baselines as benchmarks for restoration.

At the same time as older baselines may represent greater scientific uncertainties, practical challenges, and, in some cases, societal risks, restoring megafauna has high importance for biodiversity and ecosystem functioning (Fernández et al. 2017). In Europe for example, trophic rewilding is already being implemented considering deeper baselines than 1500 AD (Puttock et al. 2017, Cromsigt et al. 2018, Jepson et al. 2018). Decisions regarding the appropriate reference state must recognize this complexity, placing restoration in a wider, interdisciplinary context which also considers the socio-political and ethical implications of restoration actions.

Upscaling restoration – potential and challenges

Papers in this special issue cover from local-scale studies (Mittelman et al. 2021, Zhang et al. 2021) to continental (Segar et al. 2021, Quintero-Uribe et al. 2022) and global (Monsarrat and Svenning 2021, Storch et al. 2021, Vynne et al. 2022), highlighting a growing interest for restoration research from a broad range of spatial perspectives.

Restoration has global implications, and large-scale macroecological studies are helpful to contextualize and prioritize restoration actions (Strassburg et al. 2020). Vynne et al. (2022) take an ecoregion-based approach to identify landscapes that can retain large-mammal assemblages similar to those present five hundred years ago (1500 AD). They also identify priority ecological regions where historically intact large mammal communities could be restored through focusing restoration efforts on a reduced number of extirpated species. Over the last five centuries, the more severe loss of large mammal species occurred across much of Africa, Asia and North America. Their analysis also reveals that the recovery of 1–3 large mammal species to selected landscapes would have the greatest effect throughout northern North America, much of South America and northern Asia, but with substantial restoration potential also in many other areas. A focus on conservation and restoration of just 20 of the 298 large mammals considered in the study would considerably increase the number of ecoregions of the world with intact large mammal assemblages relative to a historical baseline of 1500 AD, i.e. prior to the onset of the intense land-use of the Anthropocene.

However, restoration is ultimately a local challenge requiring intricate knowledge of the specific socioecological context. Quintero-Uribe et al. (2022) synthesize the information from participatory scenarios across Europe, assessing the plurality of views on which elements of nature are societal priorities for restoration, using the Nature Future framework of IPBES (Pereira et al. 2020). Quintero-Uribe et al. find that scenarios matching the 'Nature as Culture' archetype, which emphasizes the role of culture in shaping nature, were most commonly explored. However, they also found that 'Nature for nature' scenarios, which emphasizes intrinsic nature values and giving space for self-regulating ecosystems, was expected to have the more positive impacts across multiple ecological components of rewilding, but could have negative impacts on some of the nature contributions to people, particular on material contributions. This poses a challenge to participatory scenarios that aim at rewilding as they may not be perceived as desirable by local communities. Quintero et al. argue that exploring scenarios with co-benefits between multiple nature perspectives and increasing the use of spatially explicit quantitative models could help in mainstreaming rewilding in local decision-making.

Zurell et al. (2021) identify gaps and biases in the use of spatially-explicit models in restoration and animal conservation. They propose a typology for models at different ecological levels, from genes to ecosystems, to support decision-making and guide restoration efforts at multiple scales. Dynamic models that explicitly account for time-dependent changes in the state of a system and transient dynamics are particularly suited to assist restoration planning and the upscaling of restoration efforts, not least given the strong interest in the short-term transient dynamics in restoration to assess if effects will be realized at sufficiently short time scales (Malhi et al. 2022). However, such models are still underused. This is due in part to the fact that spatiotemporal and time-series data that hold information on transient dynamics are only available for limited taxonomic groups and regions, making it a challenge to use dynamic models for upscaling restoration. Developing user-friendly toolboxes and set of guidelines for model building, calibration and validation, and making the most of available data, would make these models more accessible to support decision-making and restoration efforts at different spatial scales.

Outlook

Together, the studies of this Special Issue highlight how restoration initiatives in the Anthropocene should focus on conserving and promoting ecological complexity and emergent properties at multiple scales and nurturing the processes responsible for the long-term maintenance of high biodiversity levels and ecological resilience (Bullock et al. 2021, Mittelman et al. 2021, Storch et al. 2021). They emphasize the need for integrating pluralistic values of nature in restoration research and planning in order to find the required support to implement restoration at scale (Quintero-Uribe et al.

2022). Effective restoration planning also needs to consider transient dynamics and future trajectories under environmental changes to restore resilient systems for the future (Bullock et al. 2021, Zurell et al. 2021). This is inevitable given ongoing human-induced climate change, the increasing mixing of biota due to globalization, as well as the widespread human transformation of landscapes worldwide, as highlighted by the theoretical analysis of Storch et al. (2021). This suggests reducing the focus on restoring idealized visions of reference ecosystems – which is unpractical considering past ecological degradation and rapid changes towards historically unprecedented environmental and biotic states (Burke et al. 2018) and holds strong ethical baggage in ways that can perpetuate historical power imbalances (Monsarrat and Svenning 2021) – while still integrating a long-term perspective in a more dynamic manner. Looking into the past allows for better understanding of long-term ecological dynamics, biodiversity and ecosystem potentials and the ecological and evolutionary legacies of past human impact. It offers scope for overcoming shifting baseline syndrome effects to inform on opportunities for reversing range collapse and erosion of biotic communities through proactive, science-based restoration programs (Vynne et al. 2022).

Restoring ecological processes via the restoration of keystone species holds a strong potential to increase trophic complexity and to promote species richness and community resilience in the face of rising levels of anthropogenic disturbances and climate stress (Bullock et al. 2021, Storch et al. 2021), while also providing climate change adaptation and mitigation benefits (Malhi et al. 2022). This supports the adoption of rewilding at scale in policy and decision-making to fulfill the goals of the post-2020 biodiversity framework and the spirit of the declaration of the UN Decade on Ecosystem Restoration (Svenning 2020). However, an enabling policy environment is needed to facilitate actions at wide scales, and policy mechanisms at the national and international scale such as the European Common Agricultural Policy need to be adjusted for these strategies to scale-up beyond individual sites (Segar et al. 2021).

More research is needed to better understand how ecological complexity can be restored in ecosystems and across landscapes, and how this restoration manifests in emerging properties such as ecosystem functions and resilience. Empirical and theoretical work in spatial ecology, macroecology and biogeography are critical to meet these objectives. Ecological models are a powerful tool to help decision-making at various spatial scales and move from a reactive mode of management to proactive planning, taking into account different objectives and solutions and exploring a variety of scenarios (Quintero-Uribe et al. 2022) – but more effort is needed to better include them into decision making (Zurell et al. 2021). Providing social and ecological insights to inform local land-management decisions will also be a major scientific challenge for restoration efforts to materialize over the coming decade, including understanding the plurality of nature values given by society in restoration and rewilding initiatives (Quintero-Uribe et al. 2022).

The second phase of the COP15, set to take place in Kunming, China, in 2022, will hopefully see the adoption of an ambitious and effective agenda for biodiversity restoration. This is a unique chance to achieve the Convention's vision of 'living in harmony with nature by 2050' with targeted actions. It is our hope that the studies presented in this special issue will be relevant to discussions held in this context and to the future implementation of large-scale restoration.

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