1-1-2022

# Mapping and assessing the knowledge base of ecological restoration

Tina Heger
*Universität Potsdam*

Jonathan M. Jeschke
*Berlin-Brandenburgisches Institut für Biodiversitätsforschung*

Catherine Febria
*University of Windsor*

Johannes Kollmann
*Technische Universität München*

Stephen Murphy
*University of Waterloo*

*See next page for additional authors*



## Recommended Citation

Heger, Tina; Jeschke, Jonathan M.; Febria, Catherine; Kollmann, Johannes; Murphy, Stephen; Rochefort, Line; Shackelford, Nancy; Temperton, Vicky M.; and Higgs, Eric. (2022). Mapping and assessing the knowledge base of ecological restoration. *Restoration Ecology*.
https://scholar.uwindsor.ca/ibiopub/140

## Authors

Tina Heger, Jonathan M. Jeschke, Catherine Febria, Johannes Kollmann, Stephen Murphy, Line Rochefort, Nancy Shackelford, Vicky M. Temperton, and Eric Higgs

RESTORATION ECOLOGY
The Journal of the Society for Ecological Restoration

SER SOCIETY FOR ECOLOGICAL RESTORATION



THE ROYAL SOCIETY SCIENTIFIC MEETING: RESTORATION SCIENCE - RELEVANT FOR ACTION

STRATEGIC ISSUES ARTICLE

# Mapping and assessing the knowledge base of ecological restoration

Tina Heger[1,2,3,4,5,6], Jonathan M. Jeschke[2,4,5], Catherine Febria[7], Johannes Kollmann[3,8], Stephen Murphy[9], Line Rochefort[10], Nancy Shackelford[11], Vicky M. Temperton[12], Eric Higgs[11]

**Information on restoration science and practice is dispersed across large numbers of scientific papers, reports, books, and other resources, and there is a lack of synthetic approaches and of linkages between ecological theory and practice. With recent calls for scaling up ecological restoration, there is an urgent need for improving the effectiveness of restoration ecology by presenting existing knowledge in an organized and accessible form. Practitioners benefit from knowing which theories explain patterns and processes in a specific ecosystem, and scientists need an overview of empirical evidence supporting current theories. Strengthening links between restoration practice and science benefits both areas. Based on a new approach used for organizing and assessing hypotheses in invasion biology, we suggest the development of an interactive online platform that promotes the integration of restoration science and practice by (1) presenting an overview of restoration ecology; (2) mapping theoretical work relevant for ecological restoration; (3) displaying direct links to relevant publications; and (4) providing summaries of empirical evidence for ecological theories in specific settings. This online knowledge base should be developed in an open process, bringing together the restoration community with experts in semantic web and natural language processing, library scientists, web designers, and other specialists. The platform should become an evolving, searchable, openly accessible, and intuitively organized tool for future ecological restoration.**

**Key words:** conceptual overview, evidence-based restoration, interactive online platform, knowledge mapping, research synthesis, science–practice links

## Conceptual Implications

- As ecological restoration becomes a global practice with broad-scale application, available knowledge has to be collated and distributed transparently and made accessible to everyone.
- Linkages to allied fields are underexplored in restoration science and practice.
- An interactive online platform for mapping theoretical knowledge useful for ecological restoration, including existing as well as solicited and tailored meta-analyses assessing evidence for theories, can support both the science and practice of restoration.
- The proposed platform will allow inclusion of further applications, including spatial searches for projects, scientists, and practitioners.
- Recent advances in computer, information, and library science provide novel options for knowledge synthesis and representation with great potential for accelerating the science and practice of ecological restoration at local and global scales.

Author contributions: TH, EH conceived the initial ideas and led the writing; TH drafted most of the text and prepared the figures; JMJ contributed ideas about the online tool; EH, CF, JMJ, JK, SM, LR, NS, VMT contributed to the text, took part in discussions, and edited the text.

[1]Biodiversity Research/Botany, University of Potsdam, Maulbeerallee 2a, 14469 Potsdam, Germany
[2]Berlin-Brandenburg Institute of Advanced Biodiversity Research (BBIB), Königin-Luise-Strasse 2–4, 14195 Berlin, Germany
[3]Restoration Ecology, Technical University of Munich, Emil-Ramann-Strasse 6, 85350 Freising, Germany
[4]Evolutionary and Integrative Ecology, Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Müggelseedamm 310, 12587 Berlin, Germany
[5]Department of Biology, Chemistry, Pharmacy, Institute of Biology, Freie Universität Berlin, Königin-Luise-Strasse 1–3, 14195 Berlin, Germany
[6]Address correspondence to T. Heger, email t.heger@wzw.tum.de
[7]Department of Integrative Biology, Great Lakes Institute for Environmental Research, University of Windsor, Windsor, Ontario N9B 3P4, Canada
[8]Norwegian Institute of Bioeconomy Research (NIBIO), P.O. Box 115, 1431 Ås, Norway
[9]School of Environment, Resources & Sustainability, University of Waterloo, Waterloo, Ontario N2L3G1, Canada
[10]Peatland Ecology Research Group, Centre for Northern Studies, Université Laval, Quebec City, Québec G1V 0A6, Canada
[11]School of Environmental Studies, University of Victoria, Victoria, British Columbia V8W 2Y2, Canada
[12]Faculty of Sustainability, Institute of Ecology, Leuphana University Lüneburg, Universitätsallee 1, 21335 Lüneburg, Germany


doi: 10.1111/rec.13676

## Introduction

With the launch of the Decade of Ecosystem Restoration (2021–2030), the United Nations highlighted the significance of restoration to address land and water degradation, climate change, and deteriorating human livelihoods. If ecological restoration is to become a global, broad-scale practice, it is of major importance that the available knowledge is efficiently and effectively provided and used. Identifying conjectures, theories, and hypotheses that stimulate successful restoration will focus scientific efforts and will lead to a constructive feedback between restoration theory and practice. We therefore propose the coordinated development of an open-access online knowledge base for ecological restoration that will lead to an innovative research agenda for the next decade.

Restoration plays a key role at the global science-policy stage, which is both a major opportunity and a challenge, since the science of restoration is still young, inherently interdisciplinary, and directly embedded in social, cultural, political, and economic realities (Fischer et al. 2021). Since its formation in the late twentieth century, much applied research in restoration ecology has been done with the aim of identifying best practices for a multitude of restoration scenarios. Resulting outcomes have been reported from ecosystems of many kinds, e.g. drained wetlands with heavily altered soils, abandoned agricultural fields that completely lacked native flora and fauna, and recovery of endangered species or of post-mining sites with high contents of heavy metals in the soil (Chimner et al. 2017; Meli et al. 2017; Jones et al. 2018). This research, alongside the broader practice of ecological restoration, builds on knowledge from a diverse and broad spectrum of other fields, ranging from ecology to social science and local knowledge (Fig. 1).

Yet it is far from obvious exactly which areas of knowledge are useful for ecological restoration, and how best to connect theory with practice. Previous work started outlining the

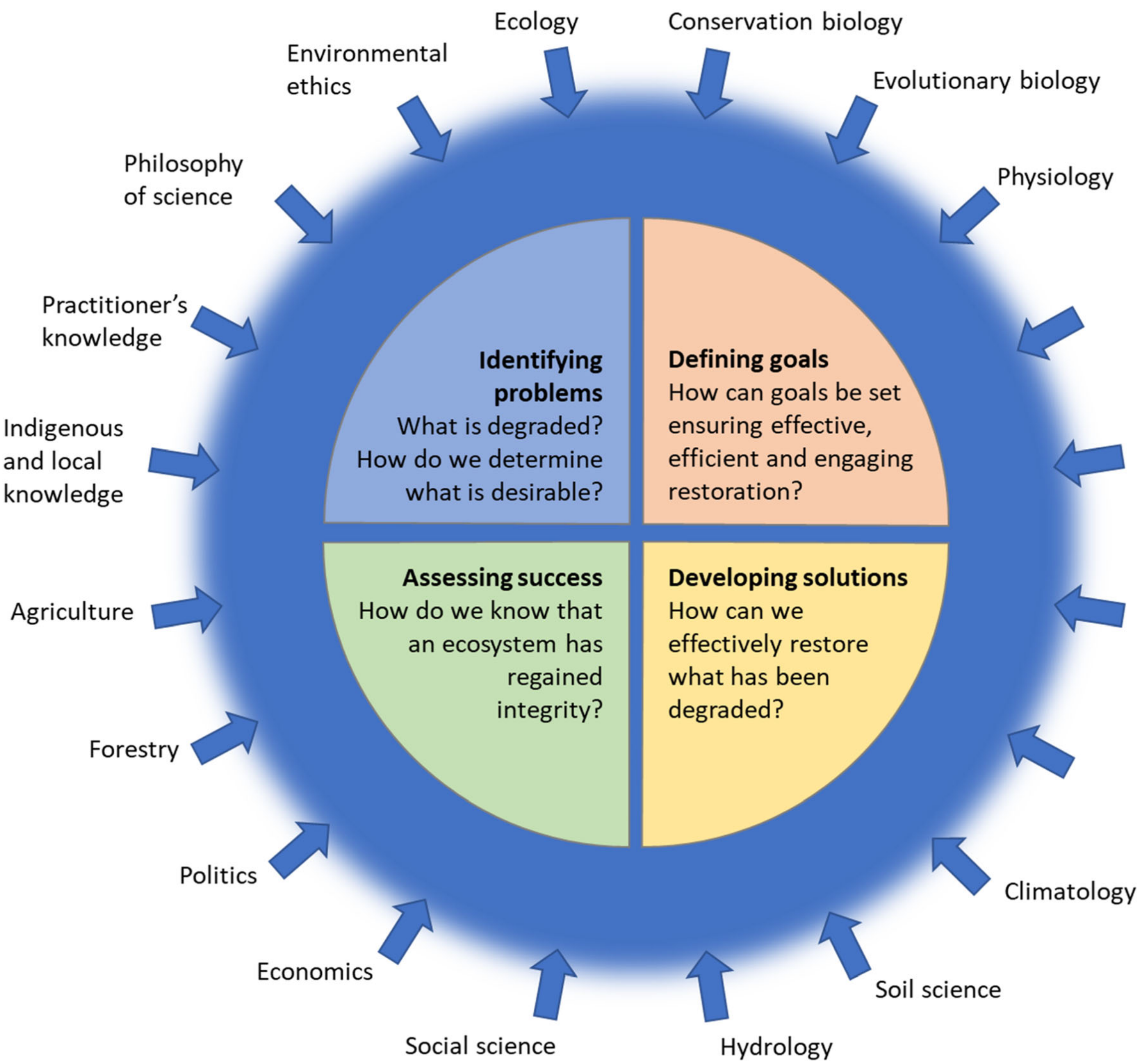


Figure 1. Research on ecological restoration focuses on four groups of questions (colored quarters in the center). Currently, it is unclear what exactly the knowledge base is that the field draws from (blurred blue background). Examples for fields that can deliver knowledge for ecological restoration are shown outside the graph; they may provide guidance for any of the four questions, that is, the position of the arrows does not indicate a link to the nearest quarters.

theoretical foundations of restoration ecology (e.g. Higgs 2003; Suding 2011; Palmer et al. 2016; Fischer et al. 2021). Despite these attempts, it remains unclear how much restoration ecology actually is rooted in ecological theory (e.g. from population or landscape ecology). Increasingly, ecological theories are being cited in the scientific restoration literature (Wainwright et al. 2018), providing useful empirical tests of some of the most common frameworks. For example, some studies rigorously test the relative influence of historical contingency (Grman et al. 2013), or the explanatory power of limiting similarity and priority effects (Soro et al. 1999; Yannelli et al. 2018; Hess et al. 2019). These types of studies remain the minority, however, and there is still uncertainty around which of the many theories (e.g. importance of priority effects, alternative vegetation states, succession, and community assembly) are most useful, and under which conditions each is most informative. Rigorous testing of hypotheses across different ecosystems, or across spatio-temporal scales, is mostly absent in the literature. A further challenge is that knowledge on restoration of terrestrial, freshwater, and marine ecosystems remains siloed in separate literatures.

Many studies have shown shortfalls in restoration in comparison with intact references (Bernhardt et al. 2005; Moreno-Mateos et al. 2012; Jones et al. 2018), further emphasizing the urgent need for consistent testing of the most promising ecological theories in restoration practice, and for synthesis of findings around individual theories that cross sites and projects. Additionally, there is a need to improve opportunities for practitioners to engage with effective theoretical frameworks to foster more direct links between restoration ecology and the practice of ecological restoration (Brudvig 2011).

It is not just the connection between theory and practice that requires development. Effective restoration is grounded in ecological and cultural knowledge, and depends on good policy guidance to mobilize "effective, efficient, and engaging" projects (Keenleyside et al. 2012; Gann et al. 2019). Building a suitable online knowledge base for scaling up restoration in the next decade will depend on reaching beyond ecological knowledge in the pursuit of solutions that work. Establishing links to social, cultural, economic, and other realms of knowledge would thus be an important step forward.

With this contribution, we advocate the development and implementation of an online portal as a first step toward revealing and further developing the knowledge foundations of ecological restoration. Opposed to traditional ways of presenting knowledge (e.g. edited volumes), an online platform will offer the opportunity of wide access and flexible updating. Online portals do not solve problems per se, but they open up potentially new ways of integration across disparate forms of knowledge that inform ecological restoration.

Our work is based on the *hierarchy-of-hypotheses* (HoH) approach developed by Heger, Jeschke, and others (Heger et al. 2021) and the idea to create interactive hypothesis networks (Jeschke et al. 2020; Jeschke et al. 2021). The HoH approach draws from the assumption that information in many cases can be structured in a hierarchical way, and that this can be helpful, e.g. for representing ecological research hypotheses (see Box 1 for more information). Hypothesis networks can be created in various ways, and provide an overview of ongoing research in a field. While the usefulness of HoHs and hypothesis networks has been demonstrated for invasion biology (Box 1), none have been created for restoration ecology so far. We suggest such approaches could serve well for providing content for an online restoration ecology portal, albeit acknowledging that the approach developed for invasion biology cannot simply be applied as it stands. In the following, we present ideas for leveraging these approaches for ecological restoration, and for building a first version of an online knowledge base for the field. We suggest tailoring this first version to the needs of scientists and other experts. Subsequent steps will then increasingly engage practitioners with their needs and knowledge.

Some clarification of terms is needed. We follow the accepted distinction between *ecological restoration* and *restoration ecology*, the latter being the scientific domain of restoration. We view *ecosystem restoration*, as featured in the UN Decade on Ecosystem Restoration, as roughly equivalent to *ecological restoration*, although ecosystem restoration often refers to restoration conducted at the level of ecosystems, whereas ecological restoration does not specify the ecological level that is targeted

**Box 1** Hierarchical network for invasion biology: A role model?

In the related discipline of invasion biology, which directs research to understanding the ecological dynamics and impacts of alien invasive species in ecosystems, an interactive hierarchical network has been implemented that summarizes hypotheses and evidence concerning the question why species can successfully establish and spread outside of their native range (*Hierarchical Network for Invasion Biology*, HNI; https://hi-knowledge.org/invasion-biology) (Jeschke et al. 2020) (Fig. 2).

To create the HNI, four steps were taken. First, major hypotheses with highest importance for the field were identified (Catford et al. 2009; Jeschke et al. 2012; Enders et al. 2018). Second, a network was created based on conceptual characterization of the most important hypotheses (Enders & Jeschke 2018); for other approaches for building networks, see Enders et al. (2019, 2020). Third, publications were systematically reviewed with the aim to assess the level of evidence for each hypothesis and the respective sub-hypotheses (Jeschke & Heger 2018). Fourth and finally, interactive visualizations were created that can be accessed online.

The third step involved the application of the *HoH* approach (Jeschke & Heger 2018; Heger et al. 2021). An HoH structures the study topics in a nested and hierarchical way, with the aim to display the complexity of hypotheses and to identify patterns in available evidence (see insert in Fig. 2). In an HoH, an overarching, major hypothesis branches into several more specific formulations, that is, sub-hypotheses, which branch again and so forth, until the desired level of specificity is reached. This nestedness allows to structure and display relationships between different fields of research.

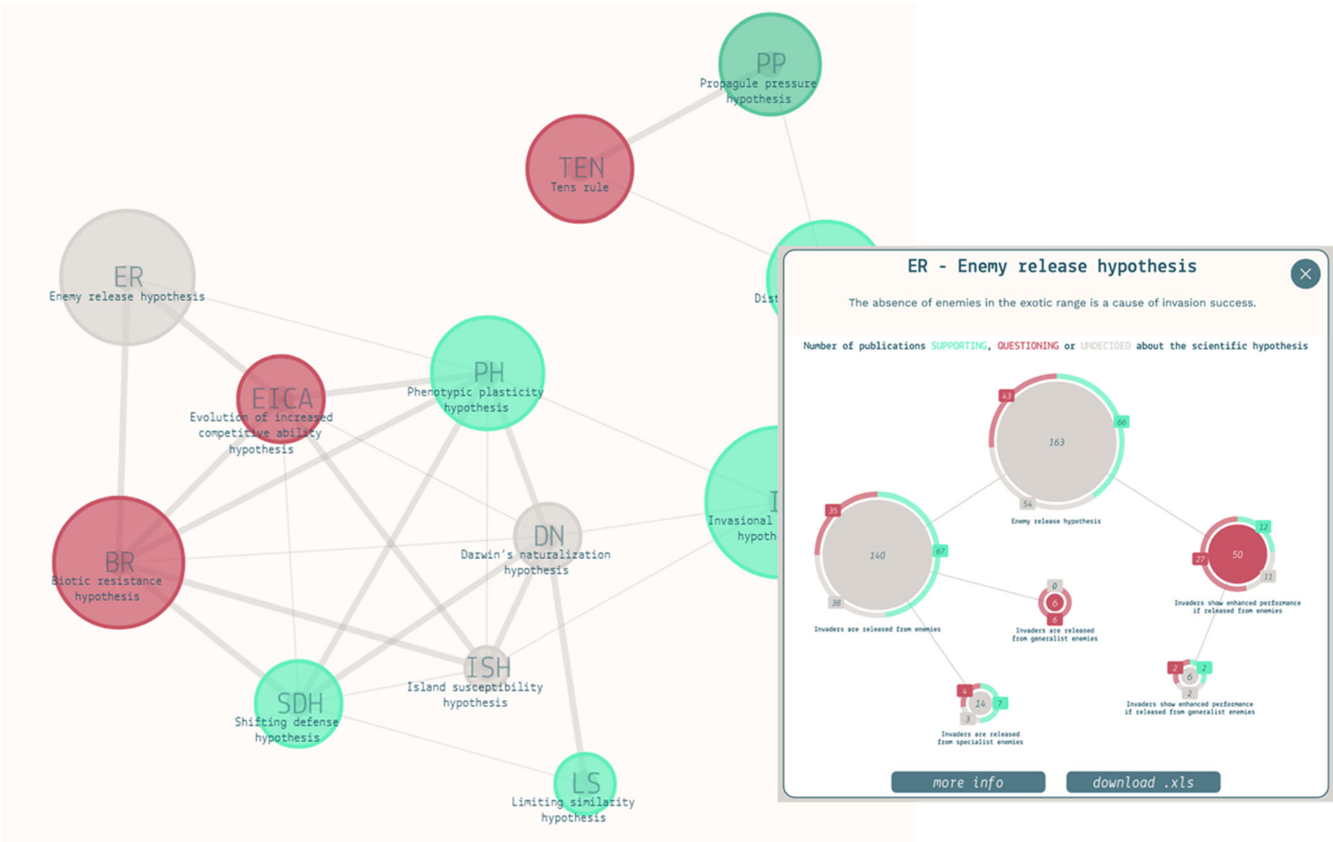


Figure 2. Screenshot hi-knowledge.org/invasion-biology. The network shows 12 invasion hypotheses and is color-coded according to the level of evidence reported for each major hypothesis in Jeschke and Heger (2018). Green, >50% of studies support this hypothesis; red, >50% of studies question it; gray, no absolute majority of studies either supporting or questioning this hypothesis. The insert shows a hierarchy-of-hypotheses for one of the hypotheses in the network, accessible by clicking on the respective hypothesis. At hi-knowledge.org/invasion-biology-large/, a larger network is shown that indicates clusters of similar hypotheses (based on Enders et al. 2020). For restoration ecology, neither HoHs nor hypotheses networks exist so far, but could in the future feed the online portal with content.

by restoration. We adopt the term "ecological restoration" as the most general and longest standing description of the science and practice of recovering from damage, degradation, and destruction at all levels from individual organisms to landscapes.

## The Evolution of Knowledge Portals

Although there are many data portals available to restoration scientists and practitioners, most provide access to raw data (e.g. species occurrences and soil data), or are generalized scientific resources (article search engines). Still, several databases and platforms provide useful and innovative functions, allowing to search for scientific publications or concrete restoration projects (Table 1). Literature search engines such as Google Scholar, Web of Science, or Scopus can help finding scientific literature covering theoretical and applied topics. More specific databases, as e.g. the U.S. National River Restoration Synthesis Database (Bernhardt et al. 2005), the Restoring Europe's Rivers Database (restorerivers.eu), the SER Restoration Project Database (ser-rrc.org/project-database), or the Land Treatments Digital Library (Pilliod & Welty 2013), allow gathering information on restoration projects or identifying suitable experts, sometimes also on successes and failures of restoration measures. Additionally, local resources exist that can help practitioners connect to each other and to get information on related projects. For example, the OBN Knowledge Network for restoration and management in the Netherlands (*Ontwikkelling + Beheer Natuurkwaliteit*) has operated since 2006, promoting greater integration of restoration activities through publications and workshops.

None of these platforms, however, specifically aims at including ecological theory or knowledge from other fields helpful for restoration. Scientific search engines like Web of Science could be used for this purpose. However, they return search results in the form of long lists, and it is difficult to identify key papers, or to figure out the most important topics that structure the field. Another issue is that these search engines are partly behind a costly paywall (Tabacaru 2019), and thus usually only accessible to researchers working in wealthy institutions. Other researchers and practitioners rarely have access to either the Web of Science or Scopus. And although Google Scholar is free to use, the underlying data are not openly available. Free online

**Table 1.** Stakeholders potentially interested in doing online research in the field of ecological restoration, and selected available discovery tools. In the cells, the functions that stakeholders may be interested in when utilizing the resources are shown. Gray color indicates that the resource provides this function only to some degree. Functions: *Overview*—get an overview of the field; *Experts*—identify experts in science or practice; *Papers*—find scientific publications on ecological theory that relate to restoration challenges; *Projects*—retrieve information on restoration projects for a certain region, ecosystem, or method; *Summaries*—create summaries of theoretical content; and *Evidence*—produce summaries of study results indicating the usefulness of methods or theory. Google Scholar: https://scholar.google.com; Web of Science: www.webofknowledge.com; Scopus: https://www.scopus.com; Open Knowledge Maps: https://openknowledgemaps.org; Connected Papers: https://www.connectedpapers.com; Research Gate: https://www.researchgate.net; GBR Coral Restoration Database: https://www.gbrcoralrestoration.org/restoration-database; Global Arid Zone Project: https://drylandrestore.com; Global Restore Project: https://globalrestoreproject.com/; Land Treatments Digital Library: https://ltdl.wr.usgs.gov/; Restor: https://www.restor.eco/; Restoration Evidence: https://www.endangeredlandscapes.org/restoration-evidence/; Restoring Europe's Rivers Database: https://restorerivers.eu/wiki/index.php?title=Main_Page; SER Project Database: https://www.ser-rrc.org/project-database/; SER Resource Database: https://chapter.ser.org/europe/knowledge-base/overview; SER Restoration Directory: https://www.ser-rrc.org/directory/; U.S. National River Restoration Synthesis Database: https://github.com/khondula/nrrss; Utah's Watershed Rest. Initiative: https://wri.utah.gov/wri/; WOCAT SLM Database: https://qcat.wocat.net/en/wocat/.

| | *Restoration Scientist* | *Restoration Practitioner* | *Decision-Maker* | *PhD or MSc Candidate* | *Ecologist* | *Scientist From Other Discipline* | *Lecturer* | *Under-Graduate Student* | *Science Journalist* | *Natural Resource Association* |
|---|---|---|---|---|---|---|---|---|---|---|
| Google Scholar | Papers | Papers | — | Papers | Papers | — | Papers | — | — | — |
| Web of Science | Papers | Papers | — | Papers | Papers | — | Papers | — | — | — |
| Scopus | Papers | Papers | — | Papers | Papers | — | Papers | — | — | — |
| Open Knowledge Maps | Papers | Papers | — | Papers | Papers | — | Papers | — | — | — |
| | — | — | Overview | Overview | Overview | Overview | Overview | Overview | Overview | Overview |
| Connected Papers | Papers | Papers | — | Papers | Papers | — | Papers | — | — | — |
| | — | — | Overview | Overview | Overview | Overview | Overview | Overview | Overview | Overview |
| Research Gate | Experts | Experts | Experts | Experts | Experts | Experts | — | — | Experts | Experts |
| GBR Coral Restoration Database | Papers | Papers | — | Papers | Papers | — | Papers | — | — | — |
| | Projects | Projects | — | Projects | Projects | — | — | — | Projects | Projects |
| | Summaries | Summaries | — | Summaries | Summaries | Summaries | Summaries | Summaries | — | — |
| | Evidence | Evidence | Evidence | Evidence | Evidence | — | Evidence | Evidence | — | Evidence |
| Global Arid Zone Project | Experts | Experts | Experts | Experts | Experts | Experts | — | — | Experts | Experts |
| | Projects | Projects | — | Projects | Projects | — | — | — | Projects | Projects |
| Global Restore Project | Projects | Projects | — | Projects | Projects | — | — | — | Projects | Projects |
| Land Treatments Digital Library | Projects | Projects | — | Projects | Projects | — | — | — | Projects | Projects |
| Restor | Projects | Projects | — | Projects | Projects | — | — | — | Projects | Projects |
| Restoration Evidence | Evidence | Evidence | Evidence | Evidence | Evidence | — | Evidence | Evidence | — | Evidence |
| Restoring Europe's Rivers Database | Projects | Projects | — | Projects | Projects | — | — | — | Projects | Projects |
| SER Project Database | Projects | Projects | — | Projects | Projects | — | — | — | Projects | Projects |
| | Summaries | Summaries | — | Summaries | Summaries | Summaries | Summaries | Summaries | — | — |
| | Evidence | Evidence | Evidence | Evidence | Evidence | — | Evidence | Evidence | — | Evidence |
| SER Resource Database | Projects | Projects | — | Projects | Projects | — | — | — | Projects | Projects |
| | Summaries | Summaries | — | Summaries | Summaries | Summaries | Summaries | Summaries | — | — |
| | Evidence | Evidence | Evidence | Evidence | Evidence | — | Evidence | Evidence | — | Evidence |
| SER Restoration Directory | Experts | Experts | Experts | Experts | Experts | Experts | — | — | Experts | Experts |
| U.S. National River Restoration Synthesis Database | Projects | Projects | — | Projects | Projects | — | — | — | Projects | Projects |
| | Evidence | Evidence | Evidence | Evidence | Evidence | — | Evidence | Evidence | — | Evidence |
| Utah's Watershed Rest. Initiative | Projects | Projects | — | Projects | Projects | — | — | — | Projects | Projects |
| WOCAT SLM Database | Projects | Projects | — | Projects | Projects | — | — | — | Projects | Projects |

services such as Open Knowledge Maps (openknowledgemaps.org) and Connected Papers (connectedpapers.com) provide new ways of visualizing research, with better possibilities for gaining an overview on relevant topics, and are thus a significant step forward. Still, these are general tools providing search results on demand, without a specific focus on ecological restoration, and not offering possibilities for establishing productive links between theory and practice.

Restoration databases to date have largely focused on pooling project information or sharing restoration methods and, less commonly, outcomes. There has been no explicit collation of theoretical frameworks into one resource, making it difficult to explore the intersection of restoration practice and the scientific theories that may best support it. Restoration ecology has investigated an enormous range of potentially relevant ecological theories that overlap and diverge in complex ways (Palmer et al. 2016). Yet any comparison or synthesis of findings within and across theories currently relies either on the time-consuming process of literature reviews or targeted specialized searches.

Based on our experience in science, teaching, and applications, we realize that restoration ecology is in urgent need of an online portal that allows mapping and assessing its theoretical foundation, similar to the *hierarchical network for invasion biology* (hi-knowledge.org/invasion-biology; Box 1). We envision a platform that provides an overview of the field of ecological restoration and allows identification of ecological theories that have proven useful. Being able to map scientific theories and their applications in restoration would allow redundancies and contradictions to be identified. Also, such a tool would support restoration scientists in prioritizing topics for investigations by providing a broad view of the available knowledge base in restoration and help to identify impactful research topics that are still underexplored. Testing across systems and scales would become much easier, and as a result, the development of a more evidence-based and better-informed restoration practice would be facilitated. Importantly, this evidence base would foster improved restoration practice.

As a first step, we suggest focusing on links between ecological theory and ecological restoration with the help of innovative searching and knowledge mapping functions. Given that in restoration projects usually multiple factors are relevant, and drivers across a landscape vary considerably, it is often necessary to integrate across terrestrial-aquatic, socio-ecological, and spatio-temporal scales. This requires in-depth theoretical knowledge covering a range of ecological systems and situations. Restoration practitioners looking for a framework for project planning (considering, e.g. how to overcome delays in recovery) could be guided to helpful publications; and practitioners working in a specific system (e.g. drained peatlands) could find theories that have proven useful for explaining processes in that specific system. Restoration scientists searching for ways to improve efficiency and effectiveness of measures would find literature that other researchers have utilized in similar situations and would find assessments of the levels of evidence for or against certain hypotheses. An intuitive, visual, and interactive platform could also help policymakers as well as students to get an overview of ecological restoration, and to understand the complexity of underlying ecological concepts.

## Toward an Online Knowledge Base for Ecological Restoration

### Major Questions in Restoration Ecology

With restoration expanding so rapidly, the dispersed nature of its knowledge is a barrier for audiences that may be looking for a bigger picture of restoration: motivated publics, policy-makers, and new practitioners. Rapid changes make it difficult for scientists and practitioners to find relevant supporting information, particularly on restoration effectiveness. It can therefore be very informative to provide a rough categorization of the topics restoration ecology is dealing with: (1) identifying problems; (2) defining goals; (3) developing solutions; and (4) assessing success (Fig. 1, colored quarters in the center). The envisioned ecological restoration online knowledge base would use this or a similar rough representation of the main questions in ecological restoration as a starting point for searches and to provide orientation for users that are new to the field.

### Mapping Underlying Theory

Restoration projects and studies regularly reference ecological studies. For example, theories in meta-population dynamics are being applied for population restoration, and assembly, succession, competition, and coexistence theories for community restoration. The complexity of theories, however, has led to a lack of linkages and difficulty in understanding the multitude of theoretical sources. A second component of the ecological restoration online knowledge base will therefore allow on-demand mapping of underlying ecological theories and hypotheses. Thus, practitioners and researchers starting a project will be able to identify potentially helpful ecological hypotheses and theories, and the respective publications.

The recently developed online resource Open Knowledge Maps (Kraker et al. 2016) can serve as a role model for building this component. Open Knowledge Maps uses natural language processing methods for identifying similarities among publications. Based on this information, knowledge maps are created that show clusters of related publications as labeled bubbles (cf. Fig. 3). At Connected Papers, a similar approach allows displaying clusters of related publications based on co-citation and bibliographic coupling. In both cases, easy access to the identified publications is provided, either via links to metadata; or directly to pdfs and datasets, if they are available. These or similar semantic search mechanisms will allow identifying theoretical work relevant for ecological restoration.

### Assessing Selected Hypotheses

Restoration science has picked up some overarching hypotheses from ecology, particularly those related to succession, assembly, and community dynamics, and has analyzed how they can contribute to successful restoration. Examples include stochastic, deterministic, and intermediate models of succession and assembly (Temperton & Hobbs 2004), filter theory and limiting

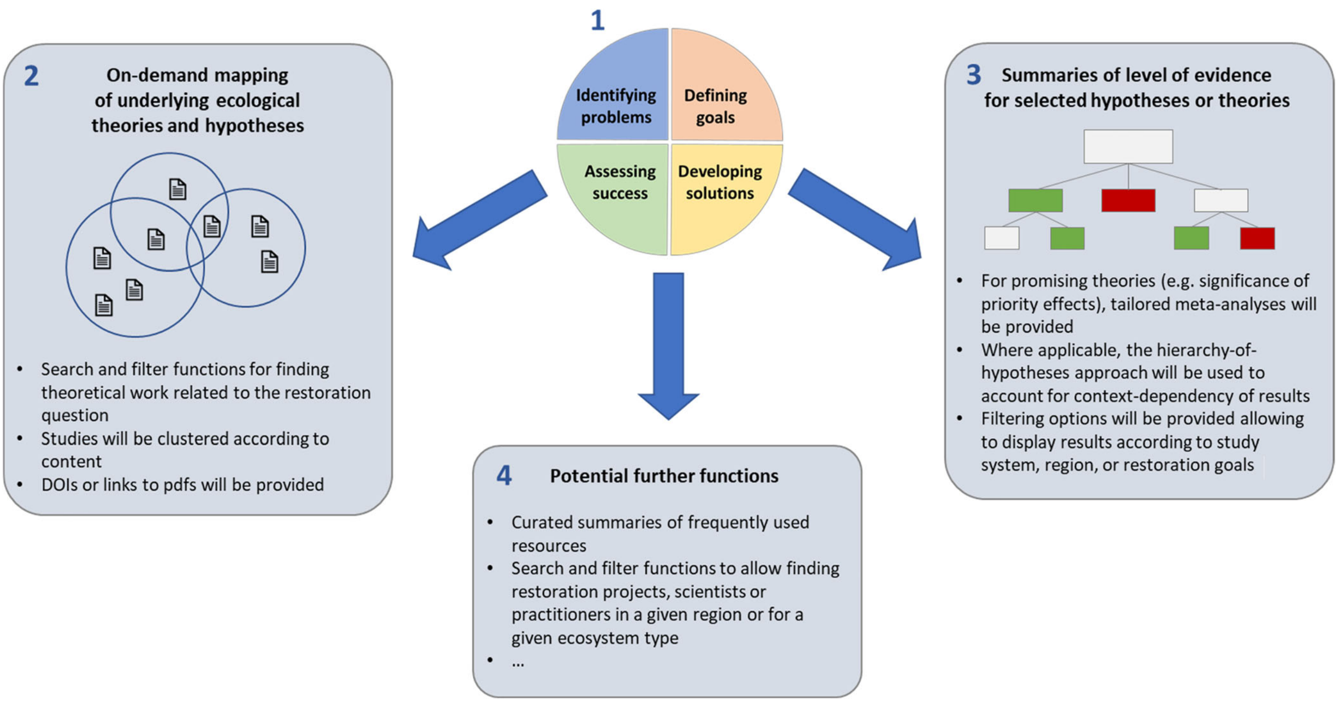


Figure 3. Outline of the suggested online platform. The platform will (1) provide a rough overview of the field of ecological restoration; (2) allow identifying ecological theory related to specific restoration questions; and (3) provide curated summaries of available evidence concerning which theories have proven useful; (4) further functions may be added in future.

similarity (Fattorini & Halle 2004; Funk et al. 2008), priority effects and historical contingency (Grman & Suding 2010; Brudvig 2011; Weidlich et al. 2017), the stress-gradient hypothesis (Fischman et al. 2019), trait-based models (Laughlin 2014; Funk & Wolf 2016), and coexistence theory (Hallett et al. 2019). Moreover, some reviews have assessed the generality of results in restoration research (e.g. Grman et al. 2013).

A goal for the third component of the envisioned ecological restoration online knowledge base will be to start a collection of meta-analyses testing how useful selected ecological theories actually are for restoration practice. Here, the role model is the *hierarchical network of invasion hypotheses* (HNI; Box 1). In cases where the design of empirical studies testing the respective theory is sufficiently homogeneous, empirical evidence will be directly synthesized using classical, statistical meta-analyses. In other cases, that is, where the hypothesis or research question of interest is rather broad, the HoH approach will be applied (Box 1) to structure empirical tests in hierarchies (Heger et al. 2021). An interactive interface will be developed that dynamically displays the level of evidence for each ecological hypothesis in a restoration context, allowing to filter results according to ecosystems. This envisioned collection of meta-analyses and HoHs could be started for example with single student projects, each feeding content into the evolving online portal.

### Additional Functions

Further functions could be added to this first version of an online knowledge base for ecological restoration. For example, similar to the search function allowing to find theoretical literature (component 1 in Fig. 3), functions for spotting researchers working in specific systems or on specific methods could be implemented. This would help users to identify and to contact experts, for example in their region. Further, the underlying body of literature could be expanded to gray literature, e.g. by linking the platform to existing restoration databases (see Table 1). This allows the implementation of search functions for finding restoration practitioners as well as specific projects. Providing visual summaries of frequently used resources, in the form of hierarchies, flow charts, or Venn diagrams, could be another useful addition (Fig. 4). Such future steps should specifically engage practitioners, addressing more and more of their needs (e.g. by displaying results in multiple languages). It is critical to have practitioners involved in the design of the knowledge base from the outset, and we envision a close interaction with the Certified Ecological Restoration Practitioners program (CERP, www.ser.org) to assure such an involvement.

## Steps Toward Implementation

The development of the platform with the described functions can be achieved by close cooperation among restoration ecologists and practitioners, computer, information and library scientists, web designers, experts in open science data management, and philosophers of science. We envision a series of workshops in which these ideas are further advanced, culminating in a project developing and implementing the platform. We plan the development and implementation as a transparent and open

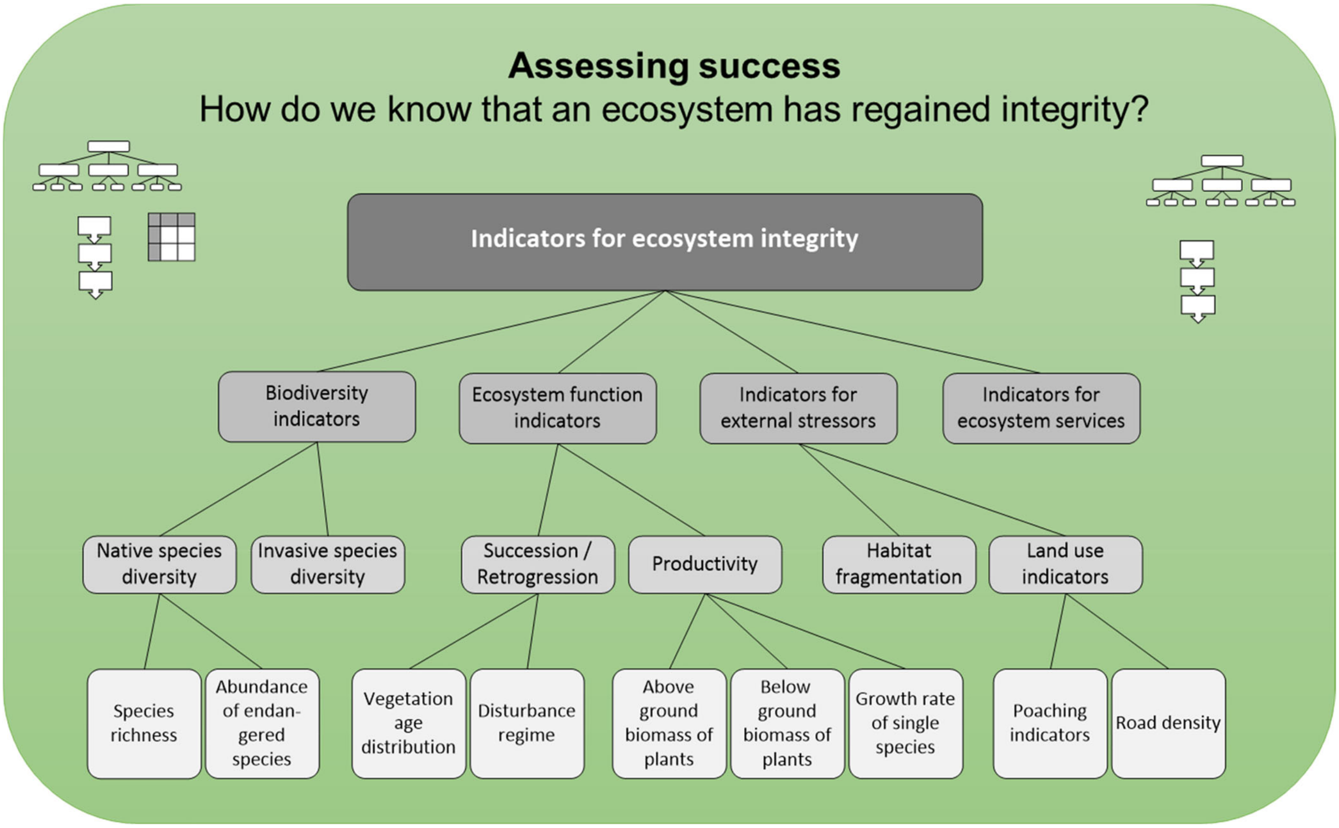


Figure 4. Example for a visual summary of frequently used resources that could be developed as a potential future component of the ecological restoration online knowledge base (see Fig. 3). Example after Keenleyside et al. (2012), with added content. The small pictograms shown in the background indicate that more such hierarchies of hypotheses, or other forms of visual summaries (matrices, flowcharts, etc.), could be added.

process, inviting contributions from the community of restoration ecologists and practitioners.

Importantly, the resulting online platform should be openly accessible and adhere to the FAIR principles for scientific data (www.go-fair.org; Wilkinson et al. 2016). Presently, much of the information that would in theory be worth including in such an online platform is not openly accessible, e.g. because it is published in a journal behind a paywall, or in proprietary reports. Mechanisms for "FAIRifying" such information are currently developed by the open science community and should be leveraged for implementing the ecological restoration online knowledge base. Assuring the quality and relevance of information is another challenge that will need to be addressed. One option is to entrust a group of experts with this task; an alternative or additional solution could be to install interactive tools (e.g. likes/dislikes by registered users). Also, it will be important to implement mechanisms right at the beginning that ensure inclusion and diversity in who is filling the knowledge base with content, enhancing, e.g. contributions from the Global South or including small NGO projects. We do not wish to entrench or amplify particular power relationships but to open up the field to be more integrative and inclusive.

A specific challenge will be to ensure that the process of developing the knowledge base will not stop once a first version is online, since continuous curation, updates, and enhancements will be necessary. It has to be discussed whether these tasks can be fulfilled by the community in a "wiki" approach, or whether there is a need for institutionalized support. Ideally, the restoration community would be strongly involved during implementation as well as for curation of data quality and continuous updates, which means that respective incentives need to be established. For practitioners engaged in SER's CERP program, a possibility could be to reward Credits (CEC) for everyone providing relevant information and data about their projects and experiences. For academics, contributions to the knowledge base could be granted the status of nanopublications with their own DOIs, so that each contribution would be citable. Ideally funding agency in the future would ask for the sharing of research data via the knowledge base as a deliverable.

We are under no illusions about the scope and ambition of this initiative. Planning such an innovative knowledge portal is one thing, but rolling it out and maintaining it is quite another. Opportunities for institutional collaboration and major long-term support will need to be found to ensure that the diverse forms of knowledge relevant for restoration are made permanently available. In the effort to scale up restoration globally, those who face the biggest restoration challenges experience a lack of resources and little access to scientific knowledge. Thus, we envision a consortium of professional organizations, national and international agencies, and philanthropic foundations to ensure success of the initiative and wide availability. The growing global movement toward open science and FAIRification of knowledge (e.g. go-fair.org) will hopefully result in better accessibility of scientific information in the near future, and the envisioned tool can both profit from and contribute to this ongoing process.

In this way, the ecological restoration online knowledge base will become an up-to-date knowledge resource that is comprehensive, intuitive, and openly accessible. It will thus provide functions previously provided by textbooks, edited volumes, or manuals, while at the same time offering a new way of searching for up-to-date scientific information and synthesis. This endeavor is of critical importance in the decade where ecological restoration will increasingly connect science and practice, and science and policy.

## Conclusions

Research in ecological restoration has to become more effective, given the challenges of up-scaling and harnessing this discipline as a major player in supporting global biodiversity and human livelihoods. Today, techniques based on artificial intelligence are improving rapidly, ongoing digitalization is transforming all layers of the global society, and awareness of the importance of openness and free accessibility of knowledge and data is increasing. Thus, we suggest that it is time for restoration ecology to seize these opportunities. An increasing number of databases and search tools are currently developed that can be and are already used for improving restoration efficiency and effectiveness, but we believe that these sources currently only scratch the surface of what would be possible. An evolving, encompassing, interactive, and multi-layered online tool is within grasp, and the start of the UN Decade of Ecological Restoration could be the catalyst to bring it to life.

## Acknowledgments

The ideas presented in this manuscript were triggered by a research visit of T.H. with E.H., funded by the Deutsche Forschungsgemeinschaft (DFG, HE 5893/7-1). T.H. and J.M.J. additionally received funding from the German Federal Ministry of Education and Research (BMBF) within the Collaborative Project "Bridging in Biodiversity Science (BIBS)" (funding number 01LC1501) and from the Volkswagen Foundation (funding number 97 863). DFG also funds TH's current position (HE 5893/8-1). C.F. is funded by Canada Research Chairs Program, NSERC Canada, V.M.T. by the State of Lower Saxony, and L.R. by Natural Sciences and Engineering Research Council of Canada (NSERC Discovery grant, no. 138097-2012). The authors thank four anonymous reviewers for their helpful comments on earlier versions of the manuscript. Open Access funding enabled and organized by Projekt DEAL.

## LITERATURE CITED

Bernhardt ES, Palmer MA, Allan JD, Alexander G, Barnas K, Brooks S, et al. (2005) Synthesizing U.S. river restoration efforts. Science 308:636–637. https://doi.org/10.1126/science.1109769

Brudvig LA (2011) The restoration of biodiversity: where has research been and where does it need to go? American Journal of Botany 98:549–558. https://doi.org/10.3732/ajb.1000285

Catford JA, Jansson R, Nilsson C (2009) Reducing redundancy in invasion ecology by integrating hypotheses into a single theoretical framework. Diversity and Distributions 15:22–40. https://doi.org/10.1111/j.1472-4642.2008.00521.x

Chimner RA, Cooper DJ, Wurster FC, Rochefort L (2017) An overview of peatland restoration in North America: where are we after 25 years? Restoration Ecology 25:283–292. https://doi.org/10.1111/rec.12434

Enders M, Havemann F, Jeschke JM (2019) A citation-based map of concepts in invasion biology. NeoBiota 47:23–42. https://doi.org/10.3897/neobiota.47.32608

Enders M, Havemann F, Ruland F, Bernard-Verdier M, Catford JA, Gómez Aparicio L, et al. (2020) A conceptual map of invasion biology: integrating hypotheses into a consensus network. Global Ecology and Biogeography 29:978–991. https://doi.org/10.1111/geb.13082

Enders M, Hütt M-T, Jeschke JM (2018) Drawing a map of invasion biology based on a network of hypotheses. Ecosphere 9:e02146. https://doi.org/10.1002/ecs2.2146

Enders M, Jeschke JM (2018) A network of invasion hypotheses. Pages 49–59. In: Jeschke JM, Heger T (eds) Invasion biology. Hypotheses and Evidence. CAB International, Wallingford, United Kingdom

Fattorini M, Halle S (2004) The dynamic environmental filter model: how do filtering effects change in assembling communities after disturbance? Pages 96–114. In: Temperton VM, Hobbs RJ, Nuttle T, Halle S (eds) Assembly rules and restoration ecology: Bridging the gap between theory and practice. Island Press, Washington, Covelo, and London.

Fischer J, Riechers M, Loos J, Martin-Lopez B, Temperton VM (2021) Making the UN Decade on Ecosystem Restoration a social-ecological endeavour. Trends in Ecology & Evolution 36:20–28. https://doi.org/10.1016/j.tree.2020.08.018

Fischman HS, Crotty SM, Angelini C (2019) Optimizing coastal restoration with the stress gradient hypothesis. Proceedings of the Royal Society B: Biological Sciences 286:20191978. https://doi.org/10.1098/rspb.2019.1978

Funk JL, Cleland EE, Suding KN, Zavaleta ES (2008) Restoration through reassembly: plant traits and invasion resistance. Trends in Ecology & Evolution 23:695–703. https://doi.org/10.1016/j.tree.2008.07.013

Funk JL, Wolf AA (2016) Testing the trait-based community framework: do functional traits predict competitive outcomes? Ecology 97:2206–2211. https://doi.org/10.1002/ecy.1484

Gann G, Mcdonald T, Aronson JC, Dixon K, Walder B, Hellett JC (2019) The SER Standards: a globally relevant and inclusive tool for improving restoration practice – a reply to Higgs et al. *Restoration Ecology*. Restoration Ecology 26:426–430. https://doi.org/10.1111/rec.12819

Grman E, Bassett T, Brudvig LA (2013) EDITOR'S CHOICE: confronting contingency in restoration: management and site history determine outcomes of assembling prairies, but site characteristics and landscape context have little effect. Journal of Applied Ecology 50:1234–1243. https://doi.org/10.1111/1365-2664.12135

Grman E, Suding KN (2010) Within-year soil legacies contribute to strong priority effects of exotics on native California grassland communities. Restoration Ecology 18:664–670. https://doi.org/10.1111/j.1526-100X.2008.00497.x

Hallett LM, Shoemaker LG, White CT, Suding KN (2019) Rainfall variability maintains grass-forb species coexistence. Ecology Letters 22:1658–1667. https://doi.org/10.1111/ele.13341

Heger T, Aguilar C, Bartram I, Braga RR, Dietl GP, Enders M, et al. (2021) The hierarchy-of-hypotheses approach: a synthesis method for enhancing theory development in ecology and evolution. Bioscience 71:337–349. https://doi.org/10.1093/biosci/biaa130

Hess MCM, Mesléard F, Buisson E (2019) Priority effects: emerging principles for invasive plant species management. Ecological Engineering 127: 48–57. https://doi.org/10.1016/j.ecoleng.2018.11.011

Higgs E (2003) Nature by design: people, natural process, and ecological restoration. MIT Press, Cambridge, MA

Jeschke JM, Enders M, Bagni M, Jeschke P, Zimmermann M, Heger T (2020). Hi-Knowledge.org, version 2.0. https://hi-knowledge.org/ (accessed 21 March 2021)

Jeschke JM, Gómez Aparicio L, Haider S, Heger T, Lortie CJ, Pyšek P, Strayer DL (2012) Support for major hypotheses in invasion biology is uneven and declining. NeoBiota 14:1–20. https://doi.org/10.3897/neobiota.14.3435

Jeschke JM, Heger T (2018) Pages 188. Invasion biology: hypotheses and evidence. CAB International, Wallingford, United Kingdom

Jeschke JM, Heger T, Kraker P, Schramm M, Kittel C, Mietchen D (2021) Towards an open, zoomable atlas for invasion science and beyond. NeoBiota 68:5–18. https://doi.org/10.3897/neobiota.68.66685

Jones HP, Jones PC, Barbier EB, Blackburn RC, Benayas JMR, Holl KD, Mccrackin M, Meli P, Montoya D, Mateos DM (2018) Restoration and repair of Earth's damaged ecosystems. Proceedings of the Royal Society B: Biological Sciences 285:20172577. https://doi.org/10.1098/rspb.2017.2577

Keenleyside K, Dudley N, Cairns S, Hall C, Stolton S (2012) Pages 133. Ecological restoration for protected areas. IUCN, Gland, Switzerland. http://data.iucn.org/dbtw-wpd/edocs/PAG-018.pdf

Kraker P, Kittel C, Enkhbayar A (2016) Open knowledge maps: creating a visual interface to the world's scientific knowledge based on natural language processing. Journal for Library Culture 4:98–103. https://doi.org/10.12685/027.7-4-2-157

Laughlin DC (2014) Applying trait-based models to achieve functional targets for theory-driven ecological restoration. Ecology Letters 17:771–784. https://doi.org/10.1111/ele.12288

Meli P, Holl KD, Rey Benayas JM, Jones HP, Jones PC, Montoya D, Moreno Mateos D (2017) A global review of past land use, climate, and active vs. passive restoration effects on forest recovery. PLoS One 12: e0171368. https://doi.org/10.1371/journal.pone.0171368

Moreno-Mateos D, Power ME, Comín FA, Yockteng R (2012) Structural and functional loss in restored wetland ecosystems. PLoS Biology 10: e1001247. https://doi.org/10.1371/journal.pbio.1001247

Palmer MA, Zedler JB, Falk DA (2016) Foundations of restoration ecology. 2nd ed. Island Press, Washington D.C.

Pilliod DS, Welty JL (2013) Land Treatment Digital Library. 806, Reston, VA

Soro A, Sundberg S, Rydin H (1999) Species diversity, niche metrics and species associations in harvested and undisturbed bogs. Journal of Vegetation Science 10:549–560. https://doi.org/10.2307/3237189

Suding KN (2011) Toward an era of restoration in ecology: successes, failures, and opportunities ahead. Annual Review of Ecology, Evolution, and Systematics 42:465–487. https://doi.org/10.1146/annurev-ecolsys-102710-145115

Tabacaru S (2019) Web of Science versus Scopus: journal coverage overlap analysis. http://hdl.handle.net/1969.1/175137

Temperton V, Hobbs RJ (2004) The search for ecological assembly rules and its relevance to restoration ecology. Pages 34–54. In: Temperton VM, Hobbs RJ, Nuttle T, Halle S (eds) Assembly rules and restoration ecology: Bridging the gap between theory and practice. Island Press, Washington, Covelo, and London.

Wainwright CE, Staples TL, Charles LS, Flanagan TC, Lai HR, Loy X, Reynolds VA, Mayfield MM (2018) Links between community ecology theory and ecological restoration are on the rise. Journal of Applied Ecology 55:570–581. https://doi.org/10.1111/1365-2664.12975

Weidlich EWA, Von Gillhaussen P, Delory BM, Blossfeld S, Poorter H, Temperton VM (2017) The importance of being first: exploring priority and diversity effects in a grassland field experiment. Frontiers in Plant Science 7:2008. https://doi.org/10.3389/fpls.2016.02008

Wilkinson MD, Dumontier M, Aalbersberg IJ, Appleton G, Axton M, Baak A, et al. (2016) The FAIR guiding principles for scientific data management and stewardship. Scientific Data 3:160018. https://doi.org/10.1038/sdata.2016.18

Yannelli FA, Karrer G, Hall R, Kollmann J, Heger T (2018) Seed density is more effective than multi-trait limiting similarity in controlling grassland resistance against plant invasions in mesocosms. Applied Vegetation Science 21:411–418. https://doi.org/10.1111/avsc.12373

*Coordinating Editor: Peter Török*

*Received: 21 May, 2021; First decision: 26 July, 2021; Revised: 9 March, 2022; Accepted: 9 March, 2022*