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REVIEW ARTICLE

Learning from scientific literature: Can indicators for measuring success be standardized in "on the ground" restoration?

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The Society for Ecological Restoration (SER) Primer identifies key ecosystem attributes for evaluating restoration outcome. Broad attribute categories could be necessary due to the large variety of restoration projects, but could make overall evaluations and assessments challenging and might hamper the development of sound and successful restoration. In this study we carry out a systematic review of scientific papers addressing evaluation of restoration outcome. We include 104 studies published after 2010 from Europe or North America, representing different types of restoration projects in terrestrial and freshwater ecosystems. We explore the main ecological and socioeconomic attributes used to evaluate restoration outcome, and related indicators and specific methods applied to measure this, in relation to ecosystem and type of restoration project. We identify a wide range of indicators within each attribute, and show that very different methods are employed to measure them. This complexity reduces the opportunity for meaningful comparison and standardization of evaluation of restoration outcome, within and between ecosystems. Socioeconomic indicators are rarely used to evaluate restoration outcome, and studies including both ecological and socioeconomic indicators are nearly absent. Based on our findings we discuss whether standardization and streamlining of indicators is useful to improve the evaluation of "on the ground" restoration, or if this is not appropriate given the diversity of goals and ecosystems involved. Species-specific traits are used in many projects and should be considered as an addition to the original SER attributes. Furthermore, we discuss the potential for restoration evaluation that encompasses not only assessment of ecological but also socioeconomic indicators.

Key words: ecological restoration, freshwater and rivers, integration, SER Primer, socioeconomic, standardize, terrestrial ecosystems

Implications for Practice

- The Society for Ecological Restoration (SER) attributes are valuable for categorizing the variety of evaluation in restoration projects, but should be expanded to include species traits and socioeconomic attributes.
- Standardization of actual measurements in the field is more relevant for "on the ground" restoration than standardization of attributes and indicators.
- For further progress of restoration on the large scale a combined top-down and bottom-up approach should be developed, where standardization of attributes (socioeconomic and ecological) is essential for the strategic planning while standardization of field measures are essential for exchange of experiences between individual restoration projects.

Introduction

Anthropogenic degradation of landscapes is the largest threat to biodiversity and ecosystems globally (Díaz et al. 2019). This has been recognized by the scientific community, as well as by nations and politicians, and has raised international commitments to the restoration of degraded land, such as the Convention on Biological Diversity Aichi targets and national and international restoration programs and initiatives (Suding et al. 2015; Chazdon et al. 2017). The focus on restoration has led to an explosion in the number of projects and scientific publications within restoration ecology. Only 36 papers reported "ecological restoration" before 1995, rising to more than 2,800 the following 20 years (Nilsson et al. 2016). Evaluation of outcome and gains from restoration is still at an early stage; the first paper in Web of Science containing "ecological restoration" and "evaluation" was published in 1995.

Author contributions: DH, BK, ME conceived the study; MOK performed the literature search and organized all data; BK carried out the additional socioeconomic search; ME analyzed data; all authors wrote the manuscript.

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However, the last decades we have seen a boost in papers on evaluation of restoration outcomes (see e.g. Wortley et al. 2013 and references therein), although the assessment of socioeconomic output is still infrequent (Aronson et al. 2010; Wortley et al. 2013; Barthelemy & Armani 2015; Browne et al. 2018).

The SER Primer underpins the identification of nine key ecosystem attributes to formulate goals for restoration (SER 2004; McDonald et al. 2016). The broad attribute categories are said to be a necessity due to the diverse types of projects carried out, variation in restoration objectives, methods of intervention, size and extent in different habitat types (McDonald et al. 2016). More specific and comparable ecological and socioeconomic indicators are needed to measure the outcome in single projects. The identification of such indicators is part of the planning stage of a project, and although the SER Primer gives some examples of relevant indicators, recent reviews reveal a seemingly infinite number of indicators are used to represent the ecosystem attributes to evaluate the outcome of restoration activities in different areas and ecosystems (Ruiz-Jaen & Aide 2005; Wortley et al. 2013). On top of this, various field protocols and methods are used for measuring each indicator.

A large diversity of indicators and methods for measuring these indicators across restoration projects is an obvious consequence of the large diversity of restoration projects. The implementation of restoration as part of regular land-use management implies the involvement of diverse groups of practitioners and managers, and consequently a need for some level of standardized instructions or guidelines. The diversity of indicators and methods represents a challenge to attempts at standardization. Standardizing of indicators and registration methods might facilitate the implementation of monitoring, and also the evaluation of restoration methods. Some level of standardization may thus improve the development of sound and successful restoration and best practice guidelines (Palmer et al. 2005; Kurth & Schirmer 2014). Best practice guidelines are appealed for by practitioners doing "on the ground" restoration (Baker & Eckerberg 2013; Hallett et al. 2013; see also e.g. The International Union for Conservation of Nature 2019). Such guidelines should ideally be based on scientific knowledge and local experience stemming from aggregated knowledge of projects and studies. A highly relevant challenge is to identify the appropriate level where such standardization can take place, and to synthesize experiences from many different studies, at a level that is still considered relevant by practitioners in individual project sites. This relevance relates to the transferability between habitats and the ability to define the trade-off between the specific/unique and the generalizability of outcome from individual studies. For the future's massive scale-up of the restoration of degraded and destroyed ecosystems (as formulated by The United Nations General Assembly's declaration 2021–2030 on the UN Decade on Ecosystem Restoration) there will be an urgent need for the transfer of knowledge from individual research studies into large-scale restoration projects and programs. This calls for strategic planning within and between countries and habitats, and some level of standardization of methods and evaluation will be a prerequisite. A review of present indicators and methods in published scientific studies is a contribution to this work. Indicators from studies not published in the scientific literature can also be relevant for future standardization and strategy development; however, ecological and socioeconomic indicators from these studies are not considered here. Including studies not published in the scientific literature in this review was considered unrealistic (as their ecological and socioeconomic output is hardly reported and mostly unavailable) and less relevant as the selection of projects would be unsystematic. The selection of such literature would be highly biased due to, for example, language barriers and limited by a lack of databases that would facilitate access to all relevant literature.

Ruiz-Jaen and Aide (2005) reviewed the use of indicators in projects applying planting or seeding to restore a site, and found that plant species richness, plant cover, and plant density were the most frequently used indicators for evaluating restoration outcome. Wortley et al. (2013), in a follow-up, reviewed the use of indicators for ecological and socioeconomic attributes in restoration projects worldwide, but did not include a review of the methods used to measure these indicators in the field, which is a significant part of potential best practice guidelines. In the present article, we review the scientific literature for projects from a broad spectrum of restoration activities to assess the indicators and methods used to evaluate restoration outcome and how the scientific literature can inform "on the ground" restoration. We cover both ecological and socioeconomic indicators and include research projects carried out in terrestrial and freshwater ecosystems. Such varying restoration types have highly different overarching goals; some are focusing on only parts of the ecosystem (physical conditions, in e.g. water quality projects, or single target species), while others are broader, focusing on the function and system (within ecosystems, society, and even the connections between). We ask the following questions:

- What are the main attributes used in performance assessment of restoration projects and do the SER attribute categories sufficiently include all indicators used?
- Which indicators are used to evaluate restoration outcome, and how are the indicators specifically measured?
- How and to what extent are ecological and socioeconomic indicators used in the same projects?
- Can the indicators and methods for measurement, assessed in this survey be standardized to meet the needs for strategic planning and overall evaluation of restoration projects?

We demonstrate the diversity of ecological and socioeconomic attributes, indicators, and methods represented. Based on these findings, we discuss the potential and relevance of standardizing and streamlining indicators and methods to improve evaluation of on-the-ground restoration. Furthermore, we discuss the potential for integration of ecological and socioeconomic indicators in restoration evaluation.

Methods

Literature Search

The literature used was obtained from the Web of Science database. The search was performed 9 February 2017. The following search terms were used: ((indicator* OR descriptor* OR parameter* OR measure*) AND (restoration* OR revegeta* OR rehabilit*) AND (evaluat* OR success* OR monitor* OR assess*) AND (Europe* OR North America*)). We restricted the search to North America and Europe to be able to assess indicators in a limited number of ecosystems. Furthermore, as restoration ecology is a relatively young scientific area, we included papers from 2010 onwards, when methods used in the field were likely to be more consistent. We obtained 819 papers. Books, book chapters, and data papers were excluded from the results. We used the Refine Results option in Web of Science to exclude papers listed under countries outside Europe and North America (Fig. S1), leaving 732 papers. Furthermore, papers that obviously belonged to nonrelevant research fields, for example medicine or computer science, were excluded (Fig. S2), resulting in 455 papers (Table S1). The remaining selection thus still included all papers from both the natural and social sciences.

An evaluated paper was relevant if restoration measures had been carried out in the study (excluding passive restoration) and actual measurements had been performed to evaluate the success of restoration. This could be ecological or socioeconomical measurements, or both. We excluded studies providing knowledge or recommendations on how restoration should be carried out or monitored (e.g. Wolter et al. 2014), and kept only papers within terrestrial or freshwater habitats.

Before evaluating the full set of abstracts, we compiled a trial-set of 10 abstracts which all authors read and scored as relevant or not relevant. We then discussed the findings to make sure we scored the full set of abstracts similarly. The abstracts were divided evenly between the authors to evaluate if the paper was relevant for the review or not. Abstracts whose relevance were difficult to determine were assigned a question mark and evaluated by another researcher.

The initial search yielded a very low number of papers including evaluation of socioeconomic attributes ($n = 1$). We therefore performed a complementary search for such papers using the following more specific terms in the end of the search string: ((indicator* OR descriptor* OR parameter* OR measure*) AND (restoration* OR revegeta* OR rehabilit*) AND (evaluat* OR success* OR monitor* OR assess*) AND (social* OR economic* OR socio* OR public* OR aesthetic OR social-ecological OR cost*)).

Table 1. Categories used to classify included papers.

Category	*Levels*
Continent	North America; Europe
Country	Country
Ecosystem	Forest; savanna; grassland; heathland; wetland; sand dune; river; other
Type of restoration project	Species restoration; habitat and/or ecosystem recovery; management of semi-natural landscape; landscape reconstruction; hydromorphology; water quality
Reference site	Yes—intact; Yes—degraded and no interventions; No
Age of restoration	Year since intervention
Years with measurements	Number of years with monitoring of restoration outcome
Attributes evaluated	Ecological; socioeconomic; integrated
Ecological attribute	Species composition; structural diversity; physical conditions; ecosystem functioning; species traits
Socioeconomic attribute	Community engagement/participation; cultural values; economic benefits; education; governance; social acceptance

Categorization of Papers

The full versions of the relevant papers were examined further to extract information about the restoration project and details about attributes, indicators, and methods used to measure restoration outcome (Table 1). We again excluded papers without measurements performed to evaluate the restoration progress. One person (ME) was responsible for a last standardization of the dataset.

For categorization of ecosystem affiliation (Table 1), we made the following choices: Forest ecosystems comprised all forest types, including riparian forests. Savannas included mixed shrub- and woodlands, whereas grasslands encompassed semi-natural grasslands, inland grasslands on sandy soil, floodplain meadows and tall- and short-grass prairie and old-fields in North America. Wetlands included peatlands, coastal and freshwater wetlands. We also constructed a category for “other” ecosystems, including agricultural lands (two cases), mining sites (one), soda pans (one), and not linked to any specific habitat (one). For case studies carried out in more than one ecosystem, we recorded all ecosystems in our database.

We based our definition of ecological attributes on SER’s standards (McDonald et al. 2016) and their key ecosystem attributes required to develop long-term goals and short-term objectives in ecological restoration (Table 1). In addition, we included a fifth category, “Species traits,” to cover restoration focused on target species, as none of the SER attributes cover this satisfactorily. Socioeconomic attribute categories were based on Hallett et al. (2013) and their proposal for social attributes (community engagement, cultural values, economic benefits, education, and governance) as well as on own research (social acceptance; e.g. Junker et al. 2007; Woolsey et al. 2007).

We classified indicators according to a predefined list based on descriptions in McDonald et al. (2016). As the ecological indicators were highly diverse, post-reading, we extended and re-defined the list of indicators for each attribute category. Furthermore, we found that defining subindicators was useful—for example, we defined different species groups as different subindicators for the indicator “species composition.” Thus, post-reading, we also revised the list of subindicators for each indicator, and finally, we re-classified the indicators and subindicators in the 104 papers according to new lists. For the socioeconomic attributes, we used the predefined list of attributes and indicators (Tables 1 & 2), and we found no need to define subindicators. Instead, for each paper, we categorized the methods used to measure the indicators.

Table 2. (a) Categorization of indicators and subindicators for each ecological attribute. The number in parenthesis refers to the number of papers (of 104 in total) using an indicator/subindicator. (b) Categorization of indicators for each socioeconomic attribute, and the methods used to measure the indicators. The definitions of attributes marked * are taken from the SER standards (McDonald et al. 2016).

Ecological Attribute	*Definition*	*Indicators*	*Subindicators*
(a)			
Species composition	Presence of desirable species, absence of undesirable species*	Species abundance (72)	Birds (5); bryophytes (3); diatoms (2); fish (8); herpetofauna (3); invertebrates (25); lichens (1); mammals (1); mycorrhiza (1); phototrophs (1); vascular plants (48)
		Species occurrence (12)	Birds (1); bryophytes (1); fungi (1); invertebrates (2); lichens (1); vascular plants (10)
		Target species occurrence (13)	Fish (2); mammals (1); vascular plants (10)
Structural diversity	Reinstate layers, food webs, spatial habitat diversity*	Density/abundance (10)	Dead wood (2); litter (1); shrub (3); tree (6)
		Functional composition (4)	Invertebrates (1); vascular plants (3)
		Habitat distribution (9)	Habitat quality (1); vegetation types (5); other/not stated (3)
		Tree size distribution (3)	
		Vegetation cover (34)	Bare ground (17); bottom layer (6); canopy (9); field layer (20); litter (7); shrub layer (10); tree layer (3)
		Vegetation height (5)	
Physical conditions	Reinstate hydrological and substrate conditions*	Bank characteristics (5)	Bank gradient (1); bank stability (1); bank structure (2); floodplain corridor (1); riparian area (1); width of riparian buffer zone (1); other/not stated (1)
		Channel characteristics (7)	Bed structure (3); channel depth (5); channel geometry (1); channel width (2); channel width variability (1); connectivity (1); cross profile (3); longitudinal profile (3); plan form (1); river bed relief (1); river bed stabilization (1); river dynamics (1); stream course development (2); other/not stated (3)
		Light availability (3)	Photosynthetically active radiation (3); other/not stated (1)
		Microclimate (2)	Humidity (1); temperature (2)
		Soil characteristics (14)	Bulk density (2); C content (4); exchangeable cations (1); Hg content (1); N content (7); organic matter content (4); P content (5); particle size (1); pH (6); soil chemistry (4); soil depth (1); soil humus content (1); soil moisture (3); soil texture (1); temperature (1); water table level (1)
		Substrate characteristics (10)	Abiotic (1); bulk density (1); organic matter content (2); P content (1); particle size (2); sediment chemistry (1); sediment moisture content (1); structures (1); substrate diversity (2); substrate type (7)
		Water chemical characteristics (6)	Algal abundance (1); alkalinity (1); N content (2); oxygen saturation (1); P content (2); pH (3); total inorganic C (1); toxins (1); water chemistry (3); water hardness (1)
		Water physical characteristics (11)	Conductivity (3); current velocity (3); dynamic feature class (1); flow pattern (4); groundwater table (1); hydromorphology (1); temperature (2); turbidity (1); water levels (3)
Ecosystem functioning	Appropriate levels of growth and productivity, reinstate nutrient cycles, decomposition, plant–animal interactions,	Carbon fluxes (1)	
		Erosion (3)	Erosion volume (1); sediment flux (1); soil erosion (1)
		Food web composition (1)	Stable isotopes (1)
		Forage quality (1)	
		Fuel load (1)	

Table 2. Continued

Ecological Attribute	*Definition*	*Indicators*	*Subindicators*
	reproduction and regeneration*	Land–water interactions (1)	Stable isotopes (1)
		Productivity (5)	Biomass production (4); net ecosystem production (1)
		Sedimentation (2)	Sediment deposition (1); sedimentation volume (1)
		Seed dispersal (1)	
Species traits	Species-specific habitat quality or population traits ensuring population viability of species in focus	Habitat quality (2)	
		Life-history traits (4)	Individual growth rate (1); individual size (1); population age structure (1); population sex ratio (1); reproduction (2)
		Population density (7)	Count survey (3); mark-recapture (1); species occurrence (1); other/not stated (2)
		Population structure (2)	Life-stage distribution (2)
		Prevalence of disease (1)	
(b)			
Community engagement	The restoration builds support and connections among the local community	Public participation (2)	Media analysis (1); process analysis (1); social–ecological network analysis (1); qualitative social survey (1)
Economic benefits	Economic benefits enhanced through ecosystem restoration	Local economy	
		Economic costs versus benefits (3)	Cost–benefit analysis (1); emergy analysis (1); actual costs of restoration measures (1)
		Ecosystem services (1)	Economic valuation methods (1)
		Resources for local livelihoods	
Social acceptance	Approval and acceptance of the restoration project	Public acceptance (3)	Media analysis (1); process analysis (1); social-ecological network analysis (1); qualitative social survey (2)
		Stakeholder group acceptance (1)	Quantitative visual preference survey (1)
Governance	Engagement, unity, or consistency of institutions with governance capacity	Unity of institutional structure (1)	Qualitative interviews (1)

Analysis of the Dataset

We analyzed the dataset descriptively to identify and illustrate the complexity of attributes, indicators, subindicators, and methods used to measure them. This complexity itself is an important aspect of our study. Furthermore, there was a low number of studies in most of our predefined categories, impeding the possibilities to do numerical analyses of the data.

We summarized the dataset in relation to ecosystem, restoration type, and ecological and socioeconomic attributes covered. Next, we investigated how many and which indicators and subindicators were used for each attribute, and when the dataset allowed, how this varied with ecosystem and restoration type. Finally, to investigate the potential for standardization, we made a thorough review of the dataset for two subindicators (species abundance of vascular plants and invertebrates) to identify the methods used to measure the subindicators in the field.

Results

General Description of the Dataset

In total, 134 papers were sorted out as relevant based on abstract (Table S1). Of these, 37 were after more careful reading deemed not relevant being review papers, conceptual papers, no restoration measures, lack of details, or outside the geographical range.

Our dataset thus included 97 papers from the original search, in addition to seven papers from the supplemental search for socioeconomic attributes (Table S1), making a total of 104 papers. Of these, 96 studies investigated indicators for ecological attributes only, six studied only socioeconomic attributes, and just two studies had an integrated approach using both ecological and socioeconomic attributes.

More than twice as many studies were carried out in Europe (74) than in North America (30). The time since restoration was implemented varied; some were ongoing, in some studies the restoration age was not stated, and in others restoration measures were implemented repeatedly. Thus, we did not use time since restoration further. The number of times an indicator was recorded within a specific project (e.g. whether restoration progress over time was recorded) varied: 29% recorded the selected indicators once, 51% recorded indicators 2–5 times, 9% recorded indicators ≥6 times, and for the remaining studies this information was lacking. The studies were almost equally divided among type of reference site used; about a third of the studies used a nondegraded site, the other third a degraded, nonrestored site, and the remaining third used no reference site.

Altogether, 92 studies treated one type of restoration project. The remaining studies had two or more restoration scopes. The most common type of restoration project was "Habitat and/or ecosystem recovery," comprising 71 studies, followed by "Hydromorphology," "Management of semi-natural landscapes," "Species restoration," "Water quality," and "Landscape reconstruction" (Fig. S3).

The most frequently studied ecosystem that reported measures was rivers (31), followed by grasslands (30), whereas the other ecosystems were more sparsely represented (Fig. S3).

Restoration projects in rivers were most diverse, including both habitat and/or ecosystem recovery, hydromorphology, species restoration, water quality, and landscape reconstruction (Fig. S3). In grasslands, projects comprised both studies of effects of management of semi-natural grasslands and habitat recovery. For the remaining habitats, habitat and/or ecosystem recovery was the main restoration purpose, and other types of projects were sparsely represented (Fig. S3).

Species composition was the most commonly used ecological attribute (82%) across ecosystems (Fig. S3) and restoration types (Fig. 1). Half of the studies (49%) used indicators for structural diversity, whereas 37% used indicators for physical conditions. Ecosystem functioning and species traits were poorly represented (Fig. 1). Altogether, 64% of the studies used

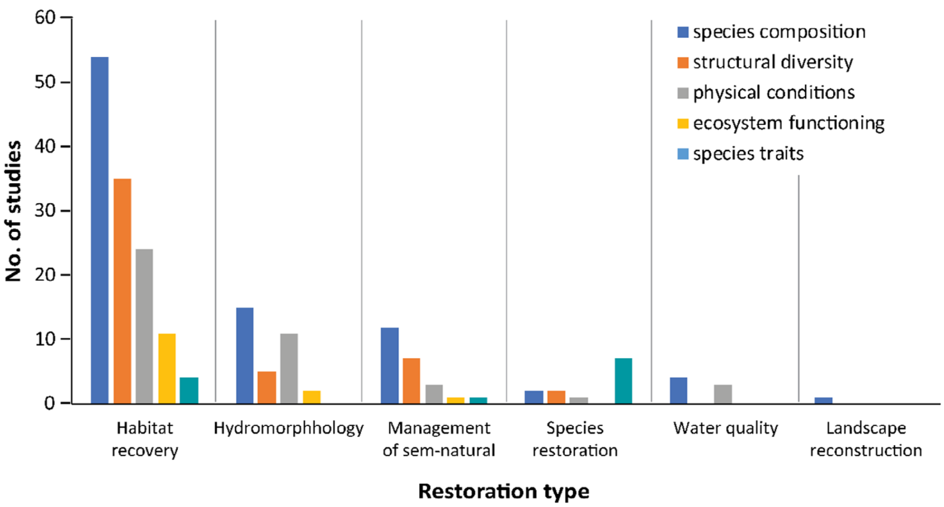

Figure 1. Ecological attributes used in relation to restoration type. As a study could include indicators from several attributes, the number of studies on the *y*-axis exceeds the number of unique studies in our data.

indicators for more than one ecological attribute. Studies carried out in rivers most often used indicators for species composition and physical conditions, whereas in terrestrial habitats, the use of indicators of structural diversity was more common, particularly in grasslands and forests (Fig. S4).

Of the eight studies including socioeconomic attributes, four used economic benefits, whereas the attribute community engagement was used in two studies, social acceptance in four studies (two times the two latter attributes were used in combination) and governance in one study. The studies were mainly broad restoration projects with multiple aims, including habitat and/or ecosystem recovery (all), hydromorphology (four), water quality (three), landscape reconstruction (two), and species restoration (one). They were mainly carried out in rivers (four), but also in grasslands (three), and sand dunes (one). The two studies using both indicators for community engagement and social acceptance were carried out in rivers, and one study combined the assessment of social acceptance and governance for grassland restoration.

Identification of Indicators and Subindicators

The categorization of indicators resulted in 31 indicators for ecological and seven for socioeconomic attributes (Table 2), spanning from 3 to 9 indicators for each ecological and 1 to 4 for each socioeconomic attribute. Even more complex was the attempt to categorize different ecological subindicators, that is, the more specific measure used to evaluate outcome (Table 2). We identified in total 127 ecological subindicators, the majority being used in only one study. Others, such as the species composition of vascular plants, were common irrespective of ecosystem or restoration type (Table 2, Fig. 2).

For the attribute species composition, indicators for species abundance were applied more often (74%) than species occurrence (presence/absence), or target species (Table 2). We defined subindicators of species composition based on taxonomic groups (Table 2) and identified 20 different subindicators. On average, 1.6 subindicators for species composition were used in a study (Fig. 3), the most common being species abundance of vascular plants, followed by species abundance of invertebrates.

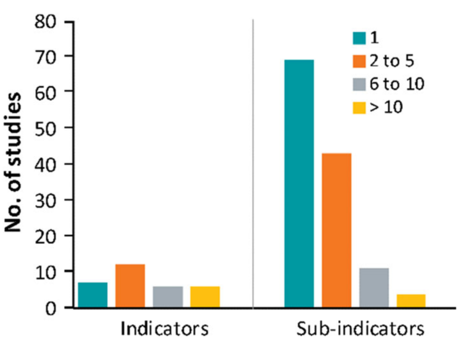

Figure 2. The frequency distribution of ecological indicators ($n = 31$) and subindicators ($n = 127$) used in 98 papers with ecological indicators included in this study.

For the attribute structural diversity, a total of six indicators and 17 subindicators were identified (Table 2). Most studies used vegetation cover, and often several subindicators representing different vegetation layers. On average, 2.2 subindicators were used per study (Fig. 3).

Indicators for physical conditions were used in 36 studies. We identified eight different indicators and 67 different subindicators (Table 2). An average of 3.6 subindicators were used (Fig. 3). Most common were subindicators related to soil or substrate characteristics, and to water physical conditions.

Ecosystem functioning was represented by only 13 studies. Productivity, sedimentation, and erosion were used in multiple studies, but except from biomass production (four studies), all subindicators were used in one study only (Table 2). Studies including indicators for ecosystem functioning used on average 1.2 subindicators (Fig. 3).

Projects focusing on species restoration used mainly indicators for species traits, including habitat quality, life-history traits, population density and structure, and prevalence of disease, with population density being the most frequent (Table 2). Because of the low number of studies of species restoration, and the diversity of organism groups studied, it was difficult to identify common sets of subindicators. Most studies used more than one subindicator (average 1.6; Fig. 3).

The low number of studies including socioeconomic attributes restricted our possibilities of drawing general conclusions about the use of indicators. Economic benefits were included in four of the eight studies, with one study measuring the actual costs of restoration, one performing cost–benefit analyses, one using economic valuation methods, and one performing emergy analysis, a system methodology able to account environmental costs and to convert them into money units. The attribute community engagement was measured by means of public participation, social acceptance by means of public acceptance, and governance by unity of institutional structure. Several of the predefined socioeconomic attributes and indicators were not represented in our dataset (Table 2).

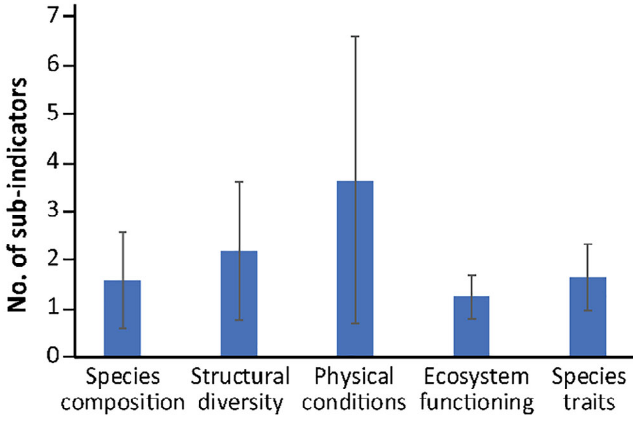

Figure 3. The mean number of subindicators used in a study, for each ecological attribute. The figure includes only studies where the attribute was used. Error bars show ±SD.

Did the Use of Attributes, Indicators, and Subindicators Vary With Restoration Type?

In rivers and grasslands, the number of studies was high enough to further examine the ecological attributes, indicators, and subindicators used to evaluate restoration outcome in relation to restoration type. The use of attributes seemed to be independent of restoration type (Figs. 4 & 5). In grasslands, indicators for species composition were used in 100% of studies of habitat recovery and 92% of studies of management of semi-natural grasslands, whereas the corresponding proportion for structural diversity indicators were 59% vs. 50%, respectively (Fig. 4A). The mean number of subindicators per attribute varied little between restoration types (Fig. 4B). Soil characteristics was the only indicator used for physical conditions, and included measurements of N, P, and C content, of pH, etc. The indicators for ecosystem functioning applied were soil erosion, forage quality, productivity, and seed dispersal, all measured in one study each.

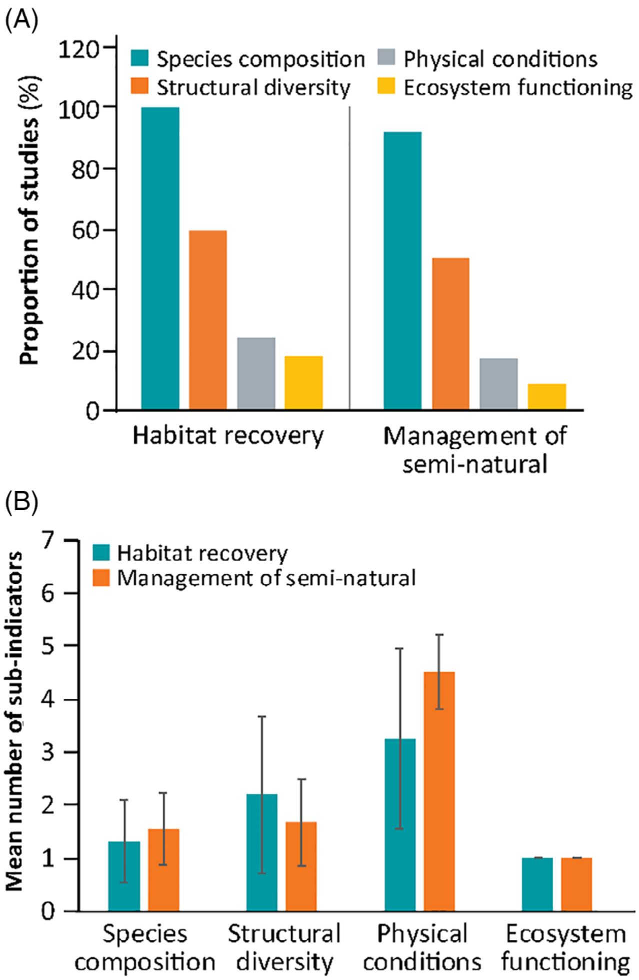

Figure 4. (A) The proportion of studies in which indicators for different ecological attributes were used in relation to restoration type in grasslands. (B) The mean number of subindicators used in a study, for each ecological attribute, for studies in grassland focusing on either habitat recovery or management of semi-natural grassland. The figure includes only studies where the attribute was used. Error bars show ±SD.

In rivers, all restoration types used species composition indicators most frequently (Fig. 5A). A total of 57% of habitat recovery and water quality studies included such indicators, and 75% of the hydromorphology studies. The use of structural diversity indicators appeared to be slightly more common in hydromorphology studies, which seemed overall to include more indicators for several ecological attributes. Although the number of subindicators measured varied little between restoration types (Fig. 5B), there seemed to be some differences in type of indicators used: bank, channel, and substrate characteristics were mainly used in hydromorphology projects, whereas water chemical characteristics were more often measured in water quality projects.

Which Methods Are Used to Measure Subindicators? Two Examples

Abundance of vascular plants was measured in 58% of the studies applying species composition indicators, including studies in all ecosystems and in the predominant restoration types. Thus,

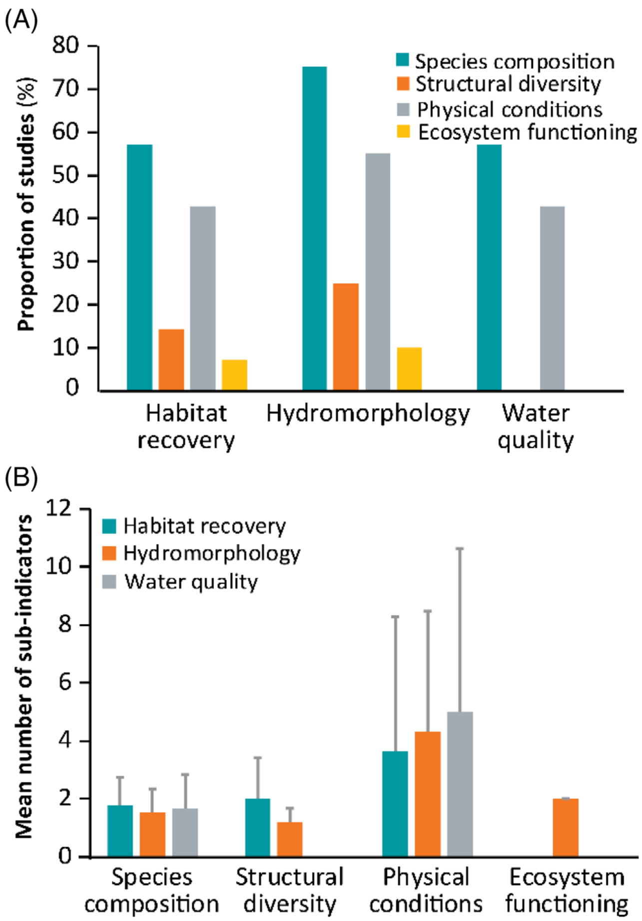

Figure 5. (A) The proportion of studies in which indicators for different ecological attributes were used in relation to restoration type in rivers. (B) The mean number of subindicators used in a study, for each ecological attribute, for studies in rivers focusing on either habitat recovery, hydromorphology, or water quality. The figure includes only studies where the attribute was used. Error bars show ±SD.

we used this subindicator to make a thorough review of the methods used in the field, as an example of the challenges of standardizing indicators, subindicators, and methods for restoration evaluation.

Vascular plants were most frequently monitored in vegetation plots (79%), whereas some studies used transects (11%) or the whole study site (11%; several methods could be used in combination, hence summing to >100%). Vegetation plots varied in size from 0.01 to 400 m^2, although most studies used a plot size of 1 m^2 (25%) or 4 m^2 (22%; Fig. 6). Plots were located systematically (38%), randomly (27%), systematically along transects (19%), subjectively (8%), or not explicitly stated (8%), within the study site. In rivers, most studies measured abundance in the study site (a river section, varying in length from 100 to 300 m), although some used transects or vegetation plots placed along transects. In all other habitats, the use of vegetation plots was most common.

Most studies used % cover as an abundance measure, but the cover scales varied from continuous (41%) to different ordinal abundance classes, including Braun-Blanquet, Daubenmire, DAFOR, and others (38%). A few studies used stem/individual density (8%) and only two studies harvested biomass. In 8% of the studies, the method used for measuring abundance could not be determined based on the paper's description. A continuous cover scale was most frequently used for relatively small vegetation plots (<16 m^2), whereas cover classes were used for both small and larger plots.

Abundance of invertebrates was measured in a total of 25 studies. The studies encompassed all ecosystems and restoration types, except species restoration. The studies focused on different groups of invertebrates; benthic invertebrates, and macroinvertebrates (11 studies; 10 in rivers and one in sand dunes), ants (one), butterflies (four), beetles (one of epigeic, floricolous, and saproxylic beetles and one of ground beetles), grasshoppers (one), leafhoppers (two), moths (three), spiders (two), and zooplankton (one), in addition to four studies on invertebrates or insects in general.

The methods used to sample invertebrates varied according to species group, and included techniques such as observation, transect walks, or hand search, traps such as pitfall traps, flight interception traps, and ultraviolet light traps, and active sampling such as sweep netting and shovel sampling. In rivers, several of the studies referred to Haase et al. (2004) for methods.

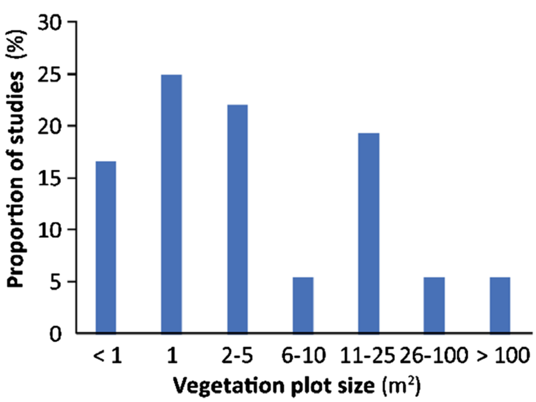

Figure 6. Frequency distribution of vegetation plot size, in 37 studies using vegetation plots to record vascular plant abundance.

Use of Ecological and Socioeconomic Attributes in the Same Study

Only two studies applied an integrated approach to measure restoration outcome by measuring both ecological and socioeconomic attributes and evaluating the outcome based on these in combination. The study by Kimball et al. (2015) was carried out in grassland habitat in the United States and recorded both species composition of vascular plants, structural diversity (vegetation cover), and economic costs. The restoration outcome was evaluated in terms of a statistical calculation of cost-effectiveness (% cover of native plants/total cost per hectare). The second study by Petúrsdottír et al. (12013*a*) compared statistically the restoration success of different treatments related to species composition with the esthetics of the different treatment plots as perceived by the local public, using a photo-based survey.

Discussion

This review of scientific literature reveals a very high diversity of ecological indicators used to evaluate restoration outcome, and an even higher diversity of methods for measuring these indicators in the field. Only a few studies, however, use socioeconomic indicators, and consequently the diversity of socioeconomic indicators reported is limited. A combined use of ecological and socioeconomic indicators in the same study is nearly absent.

Diversity of Attributes and Indicators and How These Relate to the SER Attribute Categories

Although the number of studies that carry out empirical evaluations of restoration outcome has increased in recent years (Ruiz-Jaen & Aide 2005; Wortley et al. 2013), our final dataset of 97 studies from a sample of 455 papers that met the search criteria demonstrates that reporting restoration outcome in scientific papers is yet not universal.

The key ecosystem attributes in the SER Primer (SER 2004) are useful for categorizing the variety of evaluation approaches. In line with the findings of Wortley et al. (2013), species composition is the most commonly represented attribute, regardless of ecosystem or restoration type. Structural diversity and physical conditions also occur frequently in our dataset. However, we found that the attribute ecosystem functioning is rarely represented, contrasting the results of Wortley et al. (2013), who found a higher number of studies looking at ecological processes. The distinction between physical conditions and ecosystem functioning could be difficult to operationalize, and Ruiz-Jaen and Aide (2005) merged the attributes into "ecosystem processes" in their review. Nevertheless, Ruiz-Jaen and Aide (2005) found that measures of biological interactions, in particular mycorrhizae, were more common than measures of nutrient pools and soil organic matter, which contrasts our findings. The high number of singletons of indicators and subindicators of ecosystem functioning in our dataset suggests that this attribute is by far the least standardized in restoration evaluation. The complexity and time range of ecological processes further complicate the use of such indicators, particularly in short-term evaluations.

Different species-specific indicators are found in our dataset, which do not coincide with the SER Primer attribute categories. Species trait indicators are applied in single-species restoration projects and include measures of life history and population traits or habitat occupancy. The indicator used reflects the type of organism involved. Species traits could be considered as an addition to the original SER attributes; however, any standardization of indicators must be explored against the different life histories and characteristics of single species or species groups.

In terms of the use of socioeconomic attributes, our analysis roughly confirms the results of Wortley et al. (2013) who found a share of 3.5% of the total number of studies. In our original search only 1% of the papers used socioeconomic attributes, our extended search resulted in 7.7%. The review of Hallett et al. (2013) included 203 projects registered in the Global Restoration Network (GRN) database and found that 59% of all projects had goals related to social values. However, a significantly smaller share (20%; supplementary material to Hallett et al. 2013) actually measured them in order to determine restoration success. Our review only included papers if they described actual measurements of indicators. While one fifth of the registered "on the ground" restoration projects evaluated social goals according to Hallett et al. (2013), our study shows that only very few scientific articles are reporting such efforts. Our study thus confirms that socioeconomic attributes, despite being recognized as highly relevant and urgent to evaluate, make it to a very limited degree into scientific literature. Unfortunately, Hallett et al. (2013) did not survey concrete indicators and measurements that are used for this purpose, nor reasons for the fact that only one third of the projects measured the achievement of social goals that had been set. More research is required to assess to what degree socioeconomic attributes are reported through other publication channels than the scientific literature, with potential impact on the de facto ongoing restoration.

There is a large and increasing number of articles stating and demanding that all restoration endeavors need to be seen in their respective social, economic, and political, that is, socioecological systems context and that they thus should include and assess social goals (Junker et al. 2007; Aronson et al. 2010; Petúrsdottír et al. 12013*b*; Barthelemy & Armani 2015). Our findings, especially also in relation to those of Hallett et al.'s (2013) study on projects in the GRN database, seem to indicate that social goals are still handled in a different "space" than the ecological ones, and that the problem might, that is, still be to specify and assess them (e.g. Nilsson et al. 2016). Limiting our review study to scientific literature, that is, not analyzing studies that were not published in the scientific literature, may have limited the number of cases where socioeconomic indicators were used for success evaluation. More research is needed to gain more certainty related to this question.

As also Hallett et al. (2013) state, there were for example until recently no social goals and attributes included in the SER standards (McDonald et al. 2016). However, they are addressed in the 2.0 version of the SER standards (Gann et al. 2019). We think that this will promote their employment and finally increased measurement.

What Are the Indicators and How Are They Measured?

We defined 31 indicators for ecological attributes and seven indicators for socioeconomic attributes based on our dataset. Some of these were well represented in the dataset, but in total only six of the 31 indicators were used in more than 10 of the studies, such as species abundance and vegetation cover (Table 2). Thus, across ecosystems and restoration types, the diverse use of indicators will act as a barrier for comparison and standardization of studies. Even within ecosystems there is a high diversity of indicators used for a given attribute, exemplified by six indicators representing physical conditions in rivers, in turn represented by 41 different subindicators.

The ecological indicators as defined here are broad and mostly not operative, hence the need to define subindicators, describing the variable that was actually evaluated when considering restoration progress. A total of 127 subindicators were identified, many of which were singletons, and only four were used in more than 10 studies (species abundance of vascular plants, species abundance of invertebrates, cover of field layer vegetation, cover of bare ground). This is in accordance with the finding of Ruiz-Jaen and Aide (2005) who reported plant and arthropod abundance and plant cover among the most common indicators in projects applying planting or seeding to restore a site. Measures of vegetation properties are comparably easy to carry out and are less season-dependent compared to other species groups. Indicators of ecosystem functioning and processes, on the other hand, often require high-cost and repeated measurements, and a longer time-scale for evaluating development toward restoration goals. At the same time, vegetation development is often a prerequisite for the suitability of other species and it has traditionally been in focus in ecological restoration (Perrow & Davy 2002). Vegetation composition and structure can also in some contexts be a proxy for ecosystem function (Brown & Williams 2016).

However, even if indicators related to vegetation composition and structure seem to be standard evaluation tools, the scale and methods for how these are measured in the field vary. Our review reveals how different traditions or "schools" can hamper standardization. The use of phytosociological relevés is for instance common in the study of plant communities in parts of Europe, but not in other parts or in North America, affecting choices of plot size and number and abundance measurement scales. In addition to different historic traditions (Blasi et al. 2011), standardization of indicators between different parts of the world has obvious challenges related to regional ecosystem characteristics.

Evaluation and monitoring contribute to the development of restoration, and poor evaluation reduces the efficiency and effectiveness of restoration (Nilsson et al. 2016). The low rate of repeated measurement of indicators in our study further contributes to the complications for synthesizing. Only 60% of the studies repeatedly measured the indicators, making the evaluation of the outcome of restoration interventions, even in the short term, complicated. Factors such as cost, short-term research projects, and discontinuity of staff (including researchers and other professions involved in the restoration) are plausible explanations for this. Repeated measures are essential for assessing and ranking a site's degree of recovery over time (McDonald et al. 2016).

According to the SER Primer the aim for the attributes is to demonstrate the ecosystem development "towards the intended goal or reference" (SER 2004). Restoration outcome must be related to a restoration goal, and the use of a reference condition or ecosystem to evaluate development toward this goal is considered important (e.g. Stoddard et al. 2006; McDonald et al. 2016). The goal can be the shift toward a preexisting ecosystem ("original state"), or toward a less degraded state, or even toward a new direction (White & Walker 1997; Wortley et al. 2013). The complexity of reference states is striking in our study, as the papers included use comparisons to a nondegraded site, a degraded nonrestored site, to the site itself before the restoration, or no comparison at all (in almost one third of the projects). Model predictions can be an additional approach to develop goals, for example, in large projects where controls/references are unavailable (Zedler & Callaway 1999; Rydgren et al. 2019). However, this alternative was not used in any of the papers in our study.

Combined Use of Ecological and Socioeconomic Attributes and Indicators

The need and relevance of using both ecological and socioeconomic indicators to measure success in restoration as well as to integrate them has repeatedly been highlighted (Woolsey et al. 2007; Jähnig et al. 2011; Baker & Eckerberg 2013; Hein et al. 2017; Jellinek et al. 2019). Nevertheless, we found only two studies within our sample that jointly evaluated both ecological and socioeconomic attributes. To include both types of attributes in the assessment of restoration projects has been widely demanded. Whether and in which contexts it is meaningful to actually evaluate them on common grounds is another question that might need further discussion, as for example, McDonald et al. (2019) indicate. The endeavor to lay out a standard canon of attributes and respective indicators for both ecological and social goals in the second version of the SER standards is highly promising. However, as McDonald et al. (2019) point out "in the second edition, the SER Standards will continue to acknowledge that a spectrum of potential incompatibilities between anthropocentric and ecocentric goals is likely to exist."

What Is the Potential and Relevance of Standardizing Indicators?

Ecological restoration is an expanding activity globally. The need for proper evaluation to document progress and impacts on degraded land has been clearly stated in scientific papers (e.g. Palmer et al. 2005; Wortley et al. 2013; Kurth & Schirmer 2014) and in policy documents such as the Aichi targets and the UN sustainable development goals. Monitoring and evaluation are considered as prerequisites for cost-effective and successful restoration (Nilsson et al. 2016), and measures of attributes and indicators produce the data needed for this. Consequently, the quality and comparability of the measured data set the limits for generalizing from case-specific results to general best practice guidelines. As an example, in our dataset river is the most frequent ecosystem, represented by 31 case-studies, of which 15 use indicators of physical condition. Of these, eight use indicators of water physical characteristics. However, the effect on water physical characteristics from restoration intervention is hard to interpret and generalize, as a multitude of subindicators are used and measured by different methods. Further, a large part of the "on the ground" restoration projects are never reported in scientific papers, and only evaluated in a very informal manner or not at all (Nilsson et al. 2016). Consequently, the experiences from "real" restoration activity are hard to implement in new restoration projects, so that good experiences are lost, and bad experiences repeated. To assess the indicators used in the jungle of projects not reported in the scientific literature is a highly relevant follow-up of this review.

Improved restoration could be achieved by developing some level of standard protocols in the evaluation to increase comparability and reduce arbitrariness. We identify some initiatives of standardization in our dataset. The EU Water Framework Directive (WFD) directive has developed indicators for assessing the ecological status of Europe's rivers, lakes, and groundwater (Directive 2000/60/EC), with protocols for sampling and indicator assessment. These indicators used for status assessment are frequently used also for evaluating restoration outcome, thus the work under the WFD has facilitated the standardization of indicator use in European river restoration. As another relevant case, the ClimMani working group (https://climmani.org/), established as a EU Cost Action, has focused on establishing best practice for climate change manipulation experiments, including the development of protocols for recording of indicators such as plant species composition (Halbritter et al. 2020). This could be a promising example of handbook development, narrowing into a limited number of indicators measuring methods. The employment of socioeconomic attributes and their success evaluation would in our view benefit strongly from a standard protocol for suitable indicators, as several other authors have highlighted (e.g. Woolsey et al. 2007; Kurth & Schirmer 2014).

The diversity of indicators reported in this study demonstrates that a complete standardization is neither possible nor wanted, due to the large variation of goals, ecosystem types, life forms, and physical conditions present in restoration projects. What is then the right level of standardization? Or rather, what level should be standardized? We suggest two approaches: one top-down and one bottom-up, which are not mutually exclusive but rather cover different purposes of evaluation and thus are supplementary. Restoration strategies on national levels call for a broad approach, funded in politics and policy, to fulfill national and international commitments. Such strategies need standardizations for evaluating and prioritizing between, for example, habitat types (such as the EU prioritized action framework within the habitat directive [Council directive 92/43/EEC]) or restoration of wetland carbon stock (Ministry of Climate and Environment 2011). For governments to report on these goals, a top-down standard system is needed. Such a top-down approach could be based on a modified SER-attribute system, with broad attribute categories such as habitat quality or economic benefits (McDonald et al. 2016), and with standardizations of groups of indicators, and be used for overall planning, evaluation, prioritization, and comparisons of results. However, for practitioners there is a need for bottom-up standardization of methods and field procedures to increase possibilities to compare the success of restoration actions within habitats or restoration types (Hulme 2014). The ultimate goal for successful and effective restoration should be when these bottom-up standardized methods get into an interface with the top-down strategic attributes.

An integrated link between scientific studies and on the ground interventions is needed to improve the restoration work (Howell et al. 2012; Rieger et al. 2014). Our review is based on scientific papers that only partly reflect the on the ground restoration work. The improvement and efficiency of restoration will profit from an exchange between these two traditions (Wohl et al. 2015), which in turn depends on common work toward relevant standards. The initiatives of the Water Framework Directive and the EU Cost Action ClimMani serve as good examples for this necessary process. If the scientific community should contribute to sound design and standards for measures of restoration outcome in ongoing restoration projects, the input from ongoing restoration projects should also motivate scientists for developing socioeconomic and ecological standard measures in the scientific studies. Our study has revealed that this work is so far not completed.

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Supporting Information

The following information may be found in the online version of this article:

Figure S1 Print screen picture of papers listed by countries in Web of Science's Refine results option, with all countries outside Europe and North America marked off to be excluded from the search.
Figure S2. Print screen picture of papers listed within different research categories as defined by Web of Science.
Figure S3. Types of restoration projects reporting direct measures of attributes, in relation to ecosystem.
Figure S4. Ecological attribute used in relation to ecosystem.
Table S1. All 445 papers obtained after literature search, after using the search terms (see Methods in main text) and Refine Results option (Figs. S1 & S2), and five papers extracted from additional search for socioeconomic papers (labeled SEx).

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