We discuss aspects of one of the most important issues in ecological restoration: how to evaluate restoration success. This first requires clearly stated and justified restoration goals and targets; this may seem “obvious” but in our experience, this step is often elided. Indicators or proxy variables are the typical vehicle for monitoring; these must be justified in the context of goals and targets and ultimately compared against those to allow for an evaluation of outcome (e.g. success or failure). The monitoring phase is critical in that a project must consider how the monitoring frequency and overall design will allow the postrestoration trajectories of indicators to be analyzed. This allows for real-time management adjustments—adaptive management (sensu lato)—to be implemented if the trajectories are diverging from the targets. However, as there may be large variation in early postrestoration stages or complicated (nonlinear) trajectory, caution is needed before committing to management adjustments. Ideally, there is not only a goal and target but also a model of the expected trajectory—that only can occur if there are sufficient data and enough knowledge about the ecosystem or site being restored. With so many possible decision points, we focus readers’ attention on one critical step—how to choose indicators. We distinguish generalizable and specific indicators which can be qualitative, semiquantitative, or quantitative. The generalizable indicators can be used for meta-analyses. There are many options of indicators but making them more uniform would help mutual comparisons among restoration projects.

Key words: adaptive management, ecological indicators, restoration success, restoration targets

Implications for Practice

- Definition of ecological restoration goals and a target must be explicit and justified; this must precede the selection of indicators of restoration success.
- Indicators should be easily and unambiguously evaluated.
- How many indicators? We argue that a few well-selected indicators are best; one or too many will lead to analytical or logistically based failures.
- Because detecting ecosystem recovery may require multiple decades, the choice of a few easily measured and unambiguous indicators will increase the likelihood that the monitoring will continue for the expected life of the project evaluation phase.

Introduction

How to evaluate restoration success is a core question in restoration ecology (Ruiz-Jaen & Aide 2005; Wortley et al. 2013; Gatica-Saavedra et al. 2017). Not surprisingly, there have been debates over how to define or categorize success or failure. Much of that relates to the very first critical step of setting goals. The problem is that this seems to be obscured and too tacit even today (see also Hobbs & Norton 1996; Hobbs 2007; Perring et al. 2015). Defining goals and the criteria for a successful outcome also relates to the larger debate over the proper boundaries around the definition of restoration ecology.

From our perspective, that definition should be inclusive (e.g. encompasses the domains of remediation, rehabilitation, reconciliation) (see also Society for Ecological Restoration 2004; Murphy 2018). An inclusive boundary means one can still distinguish forms of restoration ecology because their goals and expected outcomes (their definition of success) will be explicit and different. One project may be no more ambitious than the rapid stabilization of eroded sites without regard to restoring species composition. Another would be more consistent with what many probably conceive of as restoration ecology—

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1Address correspondence to K. Prach, email prach@prf.jcu.cz
2Department of Botany, Faculty of Science USB, Branišovská 1760, CZ-37005, České Budějovice, Czech Republic
3Department of Functional Ecology, Institute of Botany, Czech Academy of Sciences, Třebotí, Czech Republic
4Laboratório de Ecologia e Hidrologia Florestal, Floresta Estadual de Assis, Instituto Florestal, 19802-300, Assis, SP Brazil
5Kenyon College, Gambier, OH 43022, U.S.A.
6Department of Botany, Instituto de Biociências, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS Brazil
7Londrina State University, PR Brazil
8School of Environment, Resources & Sustainability, University of Waterloo, Waterloo, Ontario Canada

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restoration of biodiversity and ecological function to a historical, predisturbance state where both of those criteria must be justified and defined as well. Success in these cases will both be recursive—success occurs when the ecological restoration reaches its goal—but the expectations, definition, and measures of success are divergent.

This led to attempts to go beyond the earlier Society for Ecological Restoration (hereafter, SER) Primers (e.g. SER 2004) and define universal standards and practices for ecological restoration. The result was the ambitious work from McDonald et al. (2018). They used a “four-wheel concept” and a 5-star rating scale, a “recovery wheel” and a “restorative/restoration continuum” used to evaluate success. The criticisms of this approach have been detailed elsewhere (e.g. Higgs et al. 2018); for our purposes, one unheralded issue within McDonald et al. (2018) is that it did not explicate that evaluation of success must grapple with elements of subjectivity that is based on expert opinion and experience. Cipollini et al. (2005) addressed this very issue and their work is vital to our understanding of how to evaluate success.

Setting Goals and Targets as the First and Crucial Step

To cut the Gordian knot, we conceptualize a restoration goal in our review here as the desired general output of our restoration effort. Depending on the context, a goal could be (for example):

- improved landscape structure,
- a fully functional ecosystem,
- the core attributes of a functional ecosystem,
- all ecosystem services,
- only one specific ecosystem service,
- a desired community species composition,
- stabilized or increased populations and genetic diversity of a target species.

The next step is to define “ecological restoration targets” and that these should be more specific. For example, one could consider the desired expected species composition of a restored site or ecosystem or the desired and expected population demography. To define the target, the delimitation of a reference stage is important (e.g. van Andel & Aronson 2012). This reference stage (least disturbed landscape, ecosystem, community, or a vital population under environmental conditions comparable to those of the restored site) shows us the direction to which we should aim our restoration effort. Normally, the reference stage is based on existing reference sites, that is, sites that did not suffer degradation. However, a reference stage is a guide and not a template to establish the target (Higgs et al. 2014; see also Clewell & Aronson 2013 for another extensive and sophisticated discussion of references). It is advisable to have more than one reference site to account for the inherent variability of natural communities. If no reference site exists, reference conditions can be defined based on the literature and our experience; e.g. we can define the number of potential target or nontarget species that we select from various compendia (vegetation surveys, regional floras). There may be such widespread degradation that a desired alternative stable state will have to be determined by this sort of process—and this is becoming increasingly the case in the age of the Anthropocene (Murphy 2018).

In cases of severe—and often widespread—degradation, the recovery of ecosystem structure and functioning to its target will be slow. For example, coal mining presents major challenges restoring Atlantic rain forest in southern Brazil because of the initial disturbance and secondary issues like facilitating invasive species (e.g. Rocha-Nicoleite et al. 2018). One consequence in this case is that while restoration has a local forest community as a reference and target, there will need to be incremental checkpoints and progress evaluations based on initial or intermediate targets. Examples of these targets can be measurements that will not be included in the reference community, e.g. the survival of planted tree saplings or the decreasing cover of invasive species.

Reflecting on the earlier call for multiple reference sites because if reference sites with expected successional stages and trajectories are available, one has more confidence that the restored site’s trajectory is appropriate, and the target eventually can be reached. These early/intermediate targets are conceived as staging or laddered targets; they represent realistic shorter-term goals that can encourage those anxious to witness some success. Such laddered targets also help avoid measuring success against only static targets. Target (and reference) ecosystems often have nonequilibrium dynamics.

This also has the important effect of ensuring that managers set a range or “envelope” of anticipated responses that define a range of acceptable restoration measures (Heirs et al. 2016). The best practice is to (1) consult early and often with stakeholders to agree on a process, (2) use that process to set a mutually agreed upon target, and (3) reflect and ensure the process and target manages stakeholders’ expectations in terms of the pace of visible success or outcomes and considers how these can be thwarted by external factors from political interference to rapid local-scale effects from global climate change.

Defining Indicators to Measure Restoration Success

Explicating the goals and targets allow the measures of restoration success to be defined concisely (Fig. 1). While exact definitions of “indicator” seem elusive (e.g. Heink & Kowarik 2010), most readers have some notion of what this familiar term means and implies—one cannot measure everything, everywhere so one has to select representative measures in a well-designed monitoring plan. For clarity, we use the definition from Heink and Kowarik (2010); the most relevant part is quoted here:

“An indicator in ecology and environmental planning is a component or a measure of environmentally relevant phenomena used to depict or evaluate environmental conditions or changes or to set environmental goals.”

It seems easier to use indicators to measure ecosystem structure than ecosystem processes (Dale & Beyeler 2001;
Evaluation of ecological restoration success

Lindenmayer et al. 2002; Niemeijer & de Groot 2008); fortunately, ecosystem structure is often a good surrogate for most ecosystem functions (Loreau 2010). Many restoration ecology studies tend to be on vegetation-dominated ecosystems and measure some form of vegetation-related response; as such, they describe structure, most often plant species composition, species abundance or dominance, or total vegetation cover. Likely, this originates from the educational background and comfort zone of many current restoration ecologists and it is often influenced by the cost of alternative methods; however, diversification of the cadre of restoration ecologists and reduced technological costs are already changing these characteristics of restoration ecology (Murphy 2018). Kollmann et al. (2016) provide a concise review of ecosystem functions and of what indicators are being used, albeit during studies that were mostly short term: Of the 224 studies they reviewed, 26% of studies dealt with nutrient cycling, 18% with productivity, 16% with water relations, 14% with geomorphological processes, 10% with carbon sequestration, and 6% with decomposition or trophic interactions. The even bigger challenge is to measure restoration success in terms of socioeconomic or monetized outcomes (e.g. Costanza et al. 2014).

Categorizing Indicators of Success in Ecological Restoration

“Generalizable indicators” is our term for ones usable in almost every (terrestrial) project: structural characteristics (e.g. canopy cover), processes (such as carbon sequestration), or biodiversity (the number or composition of target species). Specific indicators inform specific restoration targets for particular projects, e.g. monitor the number of individuals of a target population, or the content of heavy metals in biomass, or the erosion rate.

Dale and Beyeler (2001) summarized the criteria for appropriate indicators as follows:

“Good ecological indicators should meet the following criteria: be easily measured, be sensitive to stresses on the system, respond to stress in a predictable manner, be anticipatory, predict changes that can be averted by management actions, be integrative, have a known response to natural and anthropogenic disturbances and changes over time, and have low variability in response.”

Broadly, we favor the notion that fewer well-selected indicators are better than too many, simpler (tractable) indicators are better than complicated ones, and indicators must have a testable and demonstrated mechanistic relationship to the larger ecosystem structure or process they claim to measure—by this we mean ecologists should avoid decades of “hand waving” about what an indicator supposedly measures. Indicators should be clearly interpretable by managers, politicians (as much as possible), policymakers, and as many stakeholders as possible (Kandziora et al. 2013; Gatica-Saavedra et al. 2017).

We also can define indicators in terms of their approach to measuring responses. They may be formally qualitative—especially if there is a formal examination of professional opinions and experiences (e.g. using a Delphi measure; see Murphy 2018). Most readers will be more familiar with measures that are quantitative. The resemblance between the restoration and the respective reference site can be generally expressed as the response ratio $R = \ln(x/y)$, where $x$ represents a value for the restoration site, and $y$ that for the reference site (Jones et al. 2018). We can express restoration success calculating the response ratio of any quantitative indicator. Another option is to express the scores of restoration sites in terms of percentage of reference site scores. Thus, resemblance...
of restoration sites with a reference stage is usually quantified by exact criteria, but a 100% score should not be expected (Rey Benayas et al. 2009; Suding 2011; Maron et al. 2012). The lack of 1:1 concurrence between restored and reference sites reminds us all that “perfect” restoration as an ideal or requirement is not realistic (Hilderbrand et al. 2005). Some measures are better described as semiquantitative. Some semiquantitative (ordinal) scales can be used to describe results of restoration. If contextualized clearly and properly, they can be even derived from the most basic of ordinal categorizations, e.g. successful (=1), partly successful (=0.5), unsuccessful (=0). This very approach was efficiently used in a recent meta-analysis comparing outputs of a high number of heterogeneous studies lacking common quantitative criteria (Prach & Walker 2019).

Measuring Attributes of Vegetation Structure as Indicators of Ecological Restoration

In terrestrial ecosystems, the most commonly used quantitative indicators are based on responses in vegetation structure. Vegetation structure is aptly named as it is analogous to the “skeleton” of terrestrial ecosystems; it is mostly visible, sedentary, easily observed, has knowable stage and age demographics, and is measurable on most project scales at lower sunk costs.

Vegetation structure is a useful surrogate for ecosystem attributes and ecological processes, e.g. microclimate (Milling et al. 2018), carbon storage and sequestration (Wang et al. 2011; Chazdon et al. 2016), water yield (Filoso et al. 2017), protection against soil erosion (Musick & Gillette 1990; Zhou et al. 2008; Zhang et al. 2015), improving water quality (Dosskey et al. 2010), and pollination (Cho et al. 2017). More broadly, if vegetation structure is on a trajectory to be restored to a target, it usually means restoration of composition and abundance of plant species (Liebsch et al. 2008; Suganuma & Durigan 2015), microorganisms (Banning et al. 2011), and faunal groups, such as soil fauna (Frouz et al. 2008; Dalle Laste et al. 2018), butterflies (Nyafwono et al. 2015; Shuey et al. 2017), amphibians (Díaz-García et al. 2017), reptiles (Kanowski et al. 2006), and birds (Twedt et al. 2002), will also be restored. This reflects the “Field of Dreams” hypothesis, that is, if physical habitat is restored, native species will recolonize that habitat (Palmer et al. 1997). The caveats are that relationships between vegetation and ecosystem functions or services will not be consistent across all ecosystem types, and restoration is often complicated or thwarted by exotic species invasions or dispersal limitations preclude the establishment of the desired native species.

Measures of Species Composition as Indicators in Ecological Restoration

The question posed above requires that the ecological restoration of biodiversity be the main goal; that is important to justify and establish because otherwise using species composition will not be the best approach. If it is the main goal, it is cost-effective and understandable to most stakeholders to assess success of restoration by a simple estimate of the number of native species in the restoration sites or its abundance (Reid 2015). This records spontaneously established juveniles (“natural regeneration or recruitment”) and this further indicates the reestablishment of ecological processes and self-organized sustainability or resilience of the ecosystem. This measure also is compatible with the earlier notion of having earlier targets—though usually abetted by related measures. For example, if we translocate or sow native species in ecological restoration, we can measure the species composition and the proportion of survivors as an indicator of the early success of a particular restoration measure, and community composition as an intermediate or final target.

More complex but still tractable measures related to species composition can be used. We can measure the similarity in species composition between restoration sites and reference stages (including their trajectories through the time). There are several widely used indices applied to measuring species composition (see, e.g. Kent & Coker 1992) considering both qualitative (i.e. presence-absence) and quantitative data (i.e. number or cover of the particular species)—though there is a long debate over which indices are statistically and ecologically appropriate (Booth et al. 2003). We can reduce costs and time if we can focus on species importance or dominance—if this aligns with the restoration targets. We can also assess the number or abundance of nontarget, undesired, often non-native species occurring in restoration sites. Specific targets about non-native species eradication or control can be useful in assessing ecosystem recovery.

The use of species composition has gotten more sophisticated. For example, several recent meta-analyses of ecological restoration success have used comparisons of species composition between restoration and reference sites (Barral et al. 2015; Crouzeilles et al. 2017; Meli et al. 2017; Jones et al. 2018). Still, the use of species composition as an indicator has been criticized because of its low exact predictability over time, especially in species-diverse ecosystems (Suganuma & Durigan 2015). It is also clear that we cannot expect similarity between restoration and reference sites to be higher than average similarity among reference and other similar sites in the same region. Comparing species composition demands a very precise species identification, which can be hard to achieve without trained personnel—especially in species-rich and less investigated ecosystems (Durigan & Suganuma 2015).

Measuring Indicators Means Constant Monitoring — A Common Requirement That Often Is Not Implemented

Repeated measurements of appropriate indicators of restoration success, that is, by their regular monitoring, is essential for obtaining reliable information on restoration success over time, including consideration of initial, intermediate, and final restoration targets (see above). The designs of a monitoring framework must be defined by concise questions related to the target, a proper field experimental design, a conceptual framework, and curation of data (and its integrity) via repeatable application of field protocols (Block et al. 2001; Likens & Lindenmayer 2018). The nature of how and what data are collected
Evaluation of ecological restoration success

Design indicators of restoration success

Monitor and assess restoration success

Implement restoration actions

Redesign and reconsider restoration

Plan

Research and action

Evaluate

Figure 2. Adaptive management as a response to monitoring and assessing restoration success during the process of ecological restoration.

will be dependent on spatial and temporal scales defined by the restoration target and reference. Monitoring also will provide feedback for predictions, further scientific research, and facilitate adaptations to a restoration program (Williams 2011).

Most readers can likely imagine—and probably have encountered—a situation when a restoration project seems to be successful after a few years’ monitoring, but then fails, e.g. because of invasion by non-natives. Most readers probably have witnessed another typical problem wherein there is political or stakeholder pressure to get immediate and unambiguous results when the process and outcomes of ecological restoration are highly variable initially and only clear after several decades. Funding agencies—even if mandated by legal frameworks like environmental impact assessments—fail to fund monitoring (it is not exciting enough) or a project manager is allowed to reduce or eliminate funding for budgetary or political reasons (e.g. if you are not allowed to test if there is a problem, politically, no problem then exists). The lifespan of projects can outlive the originators, so projects are orphaned. Consequently, the spatial and temporal extent of monitoring is usually a compromise—and may not be effective.

Monitoring of the selected indicators should begin before the project begins, that is, some form of Before-After-Control-Impact (BACI) design. This is often neglected and guarantees ambiguity or even failure before the project even starts (see also del Moral et al. 2007). As alluded to earlier, monitoring should usually compare ideal (reference sites), the restoration site, and still-degraded sites unless the latter’s continued existence would pose an existential threat to the restoration or general state of ecosystems (e.g. if it was a rapidly disseminating disease or pest). For most cases, the problem is already widespread and the restoration is a test of repair that is desired to be generalizable; e.g. if it is a site degraded by abandoned agriculture and harbors widespread non-native species, that scenario is so common that allowing degraded sites to remain as controls is not a threat. The need is great but the usual approach of trying to solve the problem through local or scalable restoration experiments will not immediately change an entire biome at once.

Constant monitoring can detect early warnings that the desired trajectory of the ecosystem being restored is going awry. New interventions can be designed to adjust a restoration program, or a broader program of adaptive management can be implemented (Fig. 2; see Murray & Marmorek 2003 for a more through discussion of what adaptive management really entails). The original restoration strategies, actions, and targets can be adjusted in response to monitoring. The big caution is that it again depends on the overall goal of the restoration. If it is a research experiment, one might not want to change methods. If it is research and the old methods are now moot (because, e.g. a sea-level rise has occurred), then one would keep some of the old approaches to show the clear results of that externally driven failure. One can then subdivide experimental units to include new approaches to avoid complete externally driven failure (this is a good reason to have many replicates and samples). If the goal is more of a practitioner-led one where there is a social-ecological impact and research was not on the agenda, adjustments often are made without concern because the goal is stakeholder-driven success of restoration rather than a scientifically valid experiment. This is not to say projects cannot be stakeholder driven and have good science but there are projects where one goal is the focus at the deliberate exclusion of others.

The ability to adjust to externally caused problems in the expected restoration trajectory has become even more vital given the horrendous rapid pace and intensification of local-scale impacts of global anthropogenic climate change (Murphy 2018). This does happen that fast; e.g. some of the Arctic sites one of the authors works on is subject to sea-level rise and permafrost melting so rapid that the reference sites
are permanently destroyed across a wide area and the original plans from 10 years ago are now moot (S.D. Murphy, personal communication; forthcoming manuscript). From the perspective of our simpler primer here, the benefits of an adaptive management approach (sensu lato) in restoration is that it emphasizes learning about the effectiveness of the restoration effort and adjusting the restoration strategies. This learning by doing—managers tweak restoration (and record why changes were implemented) as new knowledge emerges, both about how the ecosystem functions and biodiversity develops, and how new challenges impact restoration success. Monitoring of properly selected indicators is essential for the adaptive management to be effective in reaching restoration success.

Conclusions
Evaluation of restoration success is the crucial issue of restoration ecology and the ultimate demand of each particular restoration project. We must verify if the targets established for the project were reached or if the trajectory of the ecosystem being restored is headed in the right way. We can consider the following sequential steps in restoration of any disturbed site: setting a goal, defining a restoration target, developing the project with specific restoration actions, selecting indicators for restoration success, implementing the project, monitoring the indicators, evaluating success based on the indicators, and if needed, adopting adaptive management based on the evaluation of success. Even with this sequence, we are missing important aspects such as the perspectives of Indigenous Peoples and the broader goals related to socioeconomic aspects (Wortley et al. 2013). That provides an agenda for future primers on measuring success—we need more focus on smaller technical innovations (e.g. better measurements) but also on the bigger picture of restoration in complex socioecological systems.

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