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REVIEW ARTICLE

Measuring at all scales: sourcing data for more flexible restoration references

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Restoration has long used the reference concept as a cornerstone in setting targets, designing interventions, and benchmarking success. Following the initial applications of restoration references, however, the definition and broader relevance has been debated. Particularly in an era of directional global change, using historic or even contemporary ecosystem models has been contentious among restoration scientists and practitioners. In response, there have been calls for increasing flexibility in how references are defined and diversifying sources of data used to describe a reference. Previous frameworks suggest reference information can be drawn from sources across two main axes of time and space, covering historic to contemporary sources, and near to far spatial scales. We extend these axes by including future projections of climate and species composition and regional ecological information that is spatially disconnected from defined ecosystem types. Using this new framework, we conducted a review of restoration literature published between 2010 and 2020, extracting the temporal and spatial scales of reference data and classifying reference metrics by data type. The studies overwhelmingly focused on contemporary, ecosystem-specific references to benchmark a completed project's success. The most commonly reported reference metrics were plant-based, and contemporary reference data sources were more diverse than historical or future reference data. As global conditions continue to shift, we suggest that restoration projects would benefit by expanding reference site information to include forecasted and spatially diverse data. A greater diversity of data sources can enable higher flexibility and long-term restoration success in the face of global change.

Key words: disturbance, ecological memory, historical ecology, natural range of variation, restoration success, restoration targets, site similarity

Implications for Practice

- The restoration reference concept is a cornerstone of restoration, but its definition and role should be considered carefully.
- Reference data can be sourced across space and time, ideally matching the type of reference data with both the needs of individual projects and feasibility of data acquisition.
- A review of papers published between 2010 and 2020 of restoration science shows limited variation in reference data sources, with data primarily derived from contemporary, ecosystem-specific sources.
- More diverse reference data sources can build flexibility in goal-setting and support restoration projects to identify a higher diversity of successful outcomes in the face of rapid global change.

Introduction

In restoration ecology, the reference ecosystem is a cornerstone of both science and practice. Generally understood as the spectrum and variability of natural conditions in the target ecosystem composition, structure, and function (Kaufmann et al. 1998), the reference is often described as an essential component of pre-project planning to set management goals and define best practices (Gann et al. 2019). It is also a key component to assess project success, with post-restoration monitoring tracking the trajectory of the developing ecosystem against the reference conditions (Benayas et al. 2009; Wortley et al. 2013). However, widespread debate about the relevance of references in restoration has questioned this cornerstone, with perspectives both for and against their continued use in modern practice (e.g. Parker

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& Pickett 1997; Zedler & Callaway 1999; Duarte et al. 2009; Perring et al. 2015). Invasive species; directional change such as warming temperatures, nutrient deposition, or species extinctions; and extremities of degradation lead to barriers in both defining and attaining reference conditions (Higgs et al. 2018). As such, the complexities inherent in a socially and culturally driven practice such as restoration have resulted in explicit use of anthropogenically driven goals that may not align with traditional views of an ecosystem reference (Martin 2017).

These shifts in environmental conditions and restoration goals have proved challenging in utilizing references in restoration both conceptually, in defining the reference construct, as well as practically, in measuring reference conditions. Conceptually, recent recommendations have moved away from a singular definition for references as the historical community into a diverse medley of reference definitions (Gann et al. 2019). For instance, information on historical ecosystems is now often complemented by data on contemporary native community types under similar environmental settings (White & Walker 1997) and projections of climate change and range shifts (McDonald et al. 2016; Aronson et al. 2017). With this growing breadth of reference constructs, it is important to differentiate types of references and clarify when a specific type is appropriate to use.

Practically, setting appropriate metrics for reference communities in this era of rapid environmental change is a novel challenge. Given long temporal and large spatial patterns of ecosystem degradation, it is not unusual for a historical native reference community to have few or no acceptable modern analogs (Asbjornsen et al. 2005), even for ecosystems that cover large extents or have undergone relatively recent loss (e.g. the California Central Valley - Minnich 2008). This lack of modern analogs is commonly paired with poor historical data of community structure, composition, and function, leading to questions about how to guide restoration goal setting. In addition, the natural range of variation (Morgan et al. 1994) that may characterize some ecosystems makes comprehensive understanding difficult to achieve in short spatial or temporal windows. Restoration projects that sample within short temporal and limited spatial scales may lead to underestimations of the range of an ecosystem's composition, structure, or functioning (Jackson 2006), potentially reducing restoration efficacy.

The reference idea has a strong conceptual and theoretical foundation in the literature that has evolved through time to incorporate a higher diversity of spatial and temporal reference information. Due to various constraints faced by managers, however, the application of references in practice may diverge from theoretical ideals and academic definitions. To identify possible discrepancies, we first review the evolution of the reference concept and then conduct a formal survey of the applied scientific literature to examine how current applications of references align with contemporary recommendations in the conceptual literature. We focus on observational and experimental studies and catalog the reference concepts, as well as the data sources used to identify reference conditions. We identify common areas where the application of references may fall short of the conceptual ideal and suggest steps forward to create greater alignment and clarify contemporary treatment of references in restoration science and practice.

A Brief History of the Reference Concept

The first broad introduction of restoration and its goals was presented by Bradshaw (1983) in his address to the British Ecological Society. He reviewed the primary challenges to the "reconstruction" of ecosystems after severe disturbance with an implicit goal of creating functioning, self-sustaining ecological communities. There was little emphasis on targeting individual community or habitat types. Rather, Bradshaw focused on reconstructing "desired" components of the ecosystem and accepting that results may not align with expectations. Before the end of the decade, however, the literature had shifted to emphasize the restoration of pre-disturbance conditions (sensu disturbance as severe perturbation [Cairns Jr 1989]) as the ideal target of restoration. Around the same time, the newly founded Society of Ecological Restoration gave the first definition of restoration (since revised) that explicitly targeted a "defined, indigenous historic ecosystem" (SER 1990).

Thereafter, restoration scientists rapidly developed ideas and concepts to identify and quantify the most appropriate reference for use in practice. The biotic and abiotic characteristics of a site were often measured and described, such as hydrologic regimes that partially structured fish community composition in river systems (Toth & Anderson 1998) or historical fire regimes that shaped forest structure and composition (Moore et al. 1999). Quantifying characteristics of the reference narrowed from "desired components" of an ecosystem to focus predominantly on the structure and function of a native community (NRC (National Research Council) 1992; Bradshaw 1996). To a lesser degree, the external and internal processes (e.g., historical disturbance regimes and substrate quality) that influenced the community were also considered.

During the late 1990s and early 2000s, complex metrics of reference attributes were increasingly included in conceptual discussions, such as trophic relationships (Palmer et al. 1997), resilience (SER 2004), and sustainability (Hobbs & Norton 1996). Metrics proposed to capture structure and function often involved a combination of species diversity, lifeform distribution, productivity, soil processes, and water and nutrient cycling (e.g. Ewel 1990; Aronson et al. 1993). Quantifying these complex ecological characteristics for historical communities was largely infeasible given information and resource constraints. As a result, the concept of an appropriate reference broadened to include temporal data from historical and current data from local and regional ecosystems (Asbjornsen et al. 2005). There was also a general acceptance that ecosystem variation based on stochastic events, historic land-use, and ecosystems' range of biotic and abiotic conditions presented challenges in setting restoration targets (Palmer et al. 1997; White & Walker 1997).

Contemporary and predicted global change impacts on ecosystems challenge restoration goal-setting and the usability of reference site concepts. Global change drivers, including climate change, invasive species, and nitrogen deposition (Tylianakis et al. 2008), are often directional drivers and can shift ecosystems from their historic states, that is, the structure, function, and composition of an ecosystem that occurred at some predetermined point in the past (Radeloff et al. 2015; Dudney et al. 2018). Rising temperatures, for example, are modifying the spatial location of abiotic niches, which have and will likely continue to shift species' ranges (Thomas 2010; Bebber et al. 2013; Trant et al. 2020), modify community composition and function (Hobbs et al. 2018), and change organismal fitness (Anderson 2016). In some systems, hysteresis may emerge under directional change, shifting the system into an alternative stable state that is difficult to reverse due to changes in environmental conditions and feedbacks (Suding & Hobbs 2009).

Directional global change drivers, hysteresis effects, and the likelihood of regions experiencing no-analog climates in the relatively near future (García-López & Allué 2013) test the ability of restoration practitioners to develop effective management interventions that can reduce the negative impacts of rapid ecological change on desired ecosystem states and corresponding services. The concept of novel ecosystems emerged in response to these challenges and helped managers identify ecosystems where socio-ecological thresholds may have been crossed (Hobbs et al. 2006). These threshold shifts toward non-analog communities made it very challenging to restore to a historic reference condition (Hobbs et al. 2009), and the recommendation was to identify references that were independent of traditional reference concepts (Hobbs et al. 2009). Though some of the world's ecosystems remain relatively intact (Watson et al. 2018), the rapid emergence of novel ecosystems as well as directional global change drivers like climate change that may lead to no-analog climates challenge practitioners to consider expanding the spatial and temporal scales used to define references sites in order to develop strategies that support more adaptive outcomes.

A Framework to Accommodate a Range of Reference Concepts

Over time, the definition of reference community data has broadened. Earlier definitions emphasized "arbitrary and imperfect" ecosystem selection (Aronson et al. 1993) and current definitions include predictive modeling, local knowledge, ecosystem survey data, and historical accounts (Higgs et al. 2014). Ultimately, however, sources for reference information can be situated within two axes or dimensions of spatial and temporal information (White & Walker 1997). These reference axes continue to be extended as the concept of references has evolved, allowing broader inclusion of different information types that result in a more flexible reference model. For example, the previous fidelity to historical references has shifted, and accepted reference models can now include, or even focus on, future climate scenarios or species range predictions (Gann et al. 2019). We propose that the spatial axis (spanning local- to landscape-scales) and temporal axis (spanning past to forecasted climates and communities) provide a foundation for organizing and understanding references in restoration (Fig. 1). Reference data sources can be drawn from any or all of the intersection within these two axes. Specifically, the reference can be understood or informed by historical, contemporary, or future projections (Fig. 1, *x*-axis) and by the within-site, within-ecosystem, or multi-ecosystem landscape-scale (Fig. 1, *y*-axis).

Across the span of these axes, this framework offers strong opportunities to outline restoration goals in the context of historic community structure and composition, as well as the abiotic-biotic processes that have and will influence ecosystem trajectories and potential future scenarios. Various methods that utilize reference data from sources across this framework have already been described in the literature. Modeling successional trajectories based on ecosystem variation across human impact gradients (e.g. logging or grazing gradients) and then using a range of predicted outputs to define restoration targets (Gibbons et al. 2008), for example, can help integrate larger temporal scales with the potential outcomes of human-mediated disturbance. Combining experimental disturbance exclusion with simulation modeling to predict recovered ecosystem trajectories in deeply degraded landscapes (Bisigato et al. 2002) can help isolate realistic restoration targets, and reconstructing a timeline of historical socio-ecological landscapes to provide a spectrum of potential reference options (Balaguer et al. 2014) can help inform restoration planning.

Some recent rewilding projects in Europe (e.g. Tree 2017) introduced large herbivores as a primary restoration method. These projects lack a clear ecosystem reference in terms of a static vegetation type, but they underline the potential of rapidly

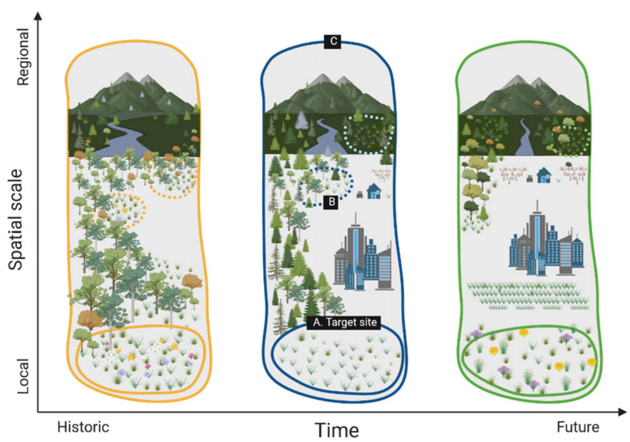

Figure 1. There are two main axes of ecological reference information—the temporal source of information, ranging from historical to predictive data (time), and the spatial source of information (spatial scale). Spatial data can be acquired within the local site targeted for restoration (A), the ecosystem-scale, focused on spatial analogs within the adjacent landscape (B), and the regional-scale, where the data often includes a broader suite of ecological information and is not tied to an individual ecosystem type (C). Temporal information can be drawn from three contexts or temporal periods: (1) historical contexts (orange outline—on left), where information may be acquired from historical surveys or accounts; (2) contemporary contexts (blue outline—in center), where information can be sourced from present day surveys or remote sensing data; or (3) future projections (green outline—on right), where information may be derived from climate scenarios or species range projections. As the spatial scale increases, the amount of potential data sources will increase, but the specificity of the data may decline.

restoring biodiverse landscapes using unconventional reference targets (historic trophic relationships). They highlight the potential to quickly and effectively restore biodiversity by accepting and even targeting naturally stochastic mosaics of open and closed landscapes (Feurdean et al. 2018) that are far from the current common European landscape. They also illustrate some of the difficulties in defining "historic" references looking backwards on the temporal axis. The term "historic" in colonial landscapes, for example, tends to imply pre-contact (Balaguer et al. 2014), with emerging emphasis on Indigenous cultural practices and management as a key component of ecological development (Turner et al. 2000). In regions where colonialism is not such a clear delineator, however, "historic" can be more ambiguous (Clewell & Aronson 2012), and in the context of rewilding has even been discussed in terms of thousands of years past (Corlett 2016). Thus, there is a push toward clearly defining what is meant by the term "history" when utilizing a historical reference (Higgs et al. 2014).

Leveraging multiple information sources can maximize the scope of conditions considered when shaping restoration targets based on a conceptual, or realized, reference ecosystem. Similarly, using a range of data sources and scales to define reference conditions can also influence how success is measured and understood. References are often used as benchmarks against which restoration sites are compared, relying primarily on spatial analogs, that is, references that are both contemporary and ecosystem-specific. Though this provides a quantitative option, it also constrains the concept of desired restoration development to a single source of reference data across the two axes, and to a potentially static view of assembly trajectories. Considering a broader suite of reference data sources allows greater flexibility in how we judge project success (Suding et al. 2015). The span of information across these axes, however, will have a variety of different potential data sources, as well as settings in which each is more or less desirable (Table 1).

The Use of the Reference Concept in the Literature Since 2010

Despite these challenges, reference communities continue to represent the internationally advocated foundation for setting restoration goals. Thus, there is a need to understand how references are being used and defined by the restoration community, and the metrics that are being most commonly measured. Here, we systematically review the modern use of the restoration reference, focusing on scientific literature published between 2010 and 2020. The systematic literature review relied on a repeatable Web of Science search using the Boolean search requirements of ((eco*) AND (rehab* OR restor* OR reveg* OR reclam*) AND (reference OR analogue)). We restricted our search fields to environmental sciences, ecology, biodiversity conservation, marine freshwater biology, zoology, forestry, water resources, fisheries, microbiology, oceanography, entomology, and mycology and ranged from January 2010 to September 2020. This search resulted in 1,812 returned citations. Given that we were focused on terrestrial, ecosystem-based reference research, we reviewed all abstracts and removed studies that focused on chemical remediation, assessments of ecological degradation, exclusively abiotic or microscopic responses, site-level restoration potential, land type and land use classifications, microcosm and laboratory experiments, and aquatic research (lakes, streams, rivers, submersed marine life). Though not a formal part of the review process, we flagged abstracts that were excluded but offered interesting insights into the use of reference communities (see Supplement S1 for a summary). This left 387 studies for review. We were most interested in how reference communities are being quantified, including the type of reference and coverage of possible spatial and temporal extent. Thus, vote-counting and overall descriptive statistics were our primary analysis methods (see Supplement S1 for details on all data collected).

We found that the vast majority of published literature used reference data as a benchmark of restoration success, with only 9% of studies conducted in order to inform planning and goal setting prior to restoration implementation. These sparse studies that did collect reference data prior to restoration actions to inform goals and planning represented some of the widest diversity of reference data sources, spanning all points of both the spatial and temporal gradients (right panel ["Goal"] in Fig. 2). In contrast, studies using reference data only to benchmark success (left panel ["Bench"] in Fig. 2) were overwhelmingly focused on contemporary, ecosystem-specific references. Likely due to the relative ease of collecting quantitative data in contemporary references, these dominated both uses of the reference concept in the literature.

In contrast, the specific metrics that were measured were the most diverse in contemporary, ecosystem-specific reference communities (Fig. 3). Plant communities dominated all reference information, but other metrics included substrate characteristics (abiotic and biotic), composition, and function of fauna communities, and in rare cases resilience-related metrics or regeneration. Contemporary references also supported the consideration of complex faunal metrics such as behavioral shifts (Lawrence et al. 2013), spatial habitat use by fauna (Rockwell & Stephens 2018), and dietary composition (Rezek et al. 2017). There were no instances when social metrics were measured in the reference communities, though some studies integrated social knowledge and preferences into restoration targets by measuring species valuation in a community (Meli et al. 2014) or incorporating place-based knowledge and experience as historical sources of reference data (Trueman et al. 2013). Metrics were typically taken on small spatial and temporal scales (Fig. 4), with 80% of studies relying on data from 1 or 2 years, and 44% of studies relying on data from only one or two distinct sites.

Implications of Modern Use

We found a consistent use of the reference concept in published restoration literature. The majority of studies (1) used post-hoc reference measurements to quantify the success of a restoration project; (2) focused on less degraded, contemporary analogs as their main data source; and (3) sampled limited numbers of reference sites or years to quantify reference conditions. There are

Table 1. Reference data sources primarily fall along two axes, increasing spatial scale (top to bottom) and shifting temporal window (left to right). Each combination of sources has different common data types, as well as ideal and problematic settings for application in restoration projects.

		Historical (pre-degradation)	*Contemporary (current)*	*Future (projected)*
Local: *within the restoration project boundaries*	*Data types*	Historic photos; written and oral history; pollen, sediment cores, seed banks	Biotic survey data; weather station data; soil and substrate data	Site-level successional trends; climate prediction models
	Ideal settings	Directional changes in climate, nutrients, or landscape context are minimal; abiotic conditions are relatively unaltered	Degradation is low and/or well-understood; place-based values are of high importance (e.g. preference for within-site sourcing)	Site-level predictions of environmental changes exist; directional change has been documented
	Problematic settings	Biotic and abiotic conditions on site have been fundamentally altered; directional changes imply new trajectory	Degradation is high and there are few or no remnants populations on site; biotic and abiotic conditions on site have been fundamentally altered; directional changes imply new trajectory	Changes unknown and likely to be non-linear
Ecosystem: *ecosystem-specific, but in locations outside of the restoration boundaries*	*Data types*	Written and oral history; weather and disturbance records; pollen, sediment cores, spores; fire scars; age structure	Biotic survey data; soil and substrate data; space-for-time successional patterns; ecosystem classification and description systems	Climate prediction models; ecosystem trajectory models
	Ideal settings	High similarity of environmental conditions between sites; directional changes in climate, nutrients, or landscape context are minimal	Low degradation areas exist regionally; low spatial/temporal variability; high similarity of biotic and abiotic conditions with regional sites	Directional change has been documented; ecosystem crosses existing climate gradients
	Problematic settings	Biotic and abiotic conditions on site have been fundamentally altered; directional changes imply new trajectory	High interannual variability and/or spatial heterogeneity requires high levels of data; biotic and abiotic conditions on site do not match contemporary communities; directional changes imply new trajectory	Poor predictions for changes exist; rare or threatened ecosystems; specific habitat or ecocultural targets require ecosystem specificity
Region: *across a spectrum of native ecosystems*	*Data types*	Museum data and land surveys; weather and disturbance records; written and oral history	Species lists; species range distributions; landscape composition and structure data; climate data	Climate prediction models; climate envelope models; trait and niche data
	Ideal settings	Lack of ecosystem-specific information; highly altered biotic and abiotic conditions on project site	Lack of ecosystem-specific information; high spatial or temporal variability within potential target ecosystem; uniformity or gradual gradients in major ecosystem types support heterogeneous composition, structure, and function	Regional climate gradients exist; broad-scale changes have been documented; fine-scale changes are poorly understood
	Problematic settings	Alternative stable states are present (e.g. shrubland vs. grassland) with one more desirable than another; rare or threatened ecosystems; specific habitat or ecocultural targets require ecosystem specificity		

clear pragmatic reasons that could be driving these outcomes. Scientific publications are often founded on analyzing treatment outcomes (leading to more post-hoc studies) with quantitative comparisons (most easily accessible in contemporary analogs) in a scientific field where resources are constrained (leading to limitations on sample size). However, such overwhelming dominance in the literature by one perspective on reference ecosystems both reflects and influences the development of the

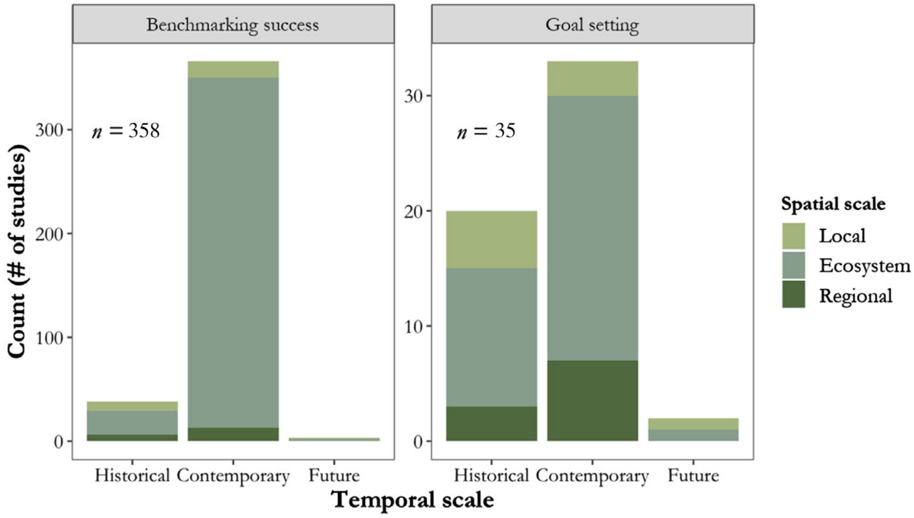

Figure 2. The use of references in goal setting and benchmarking success. Left panel illustrates the number of studies that used reference sites to benchmark success and right panel illustrates the number of studies that used reference information in goal setting. Bars represent the temporal scale of the reference (*x*-axis; temporal scale) and green shades illustrate the spatial scale of the reference information. The majority of studies focused on references as benchmarks of success (left panel, $n = 358$) compared to goal setting ($n = 35$). Note the change in scale on the *x*-axis.

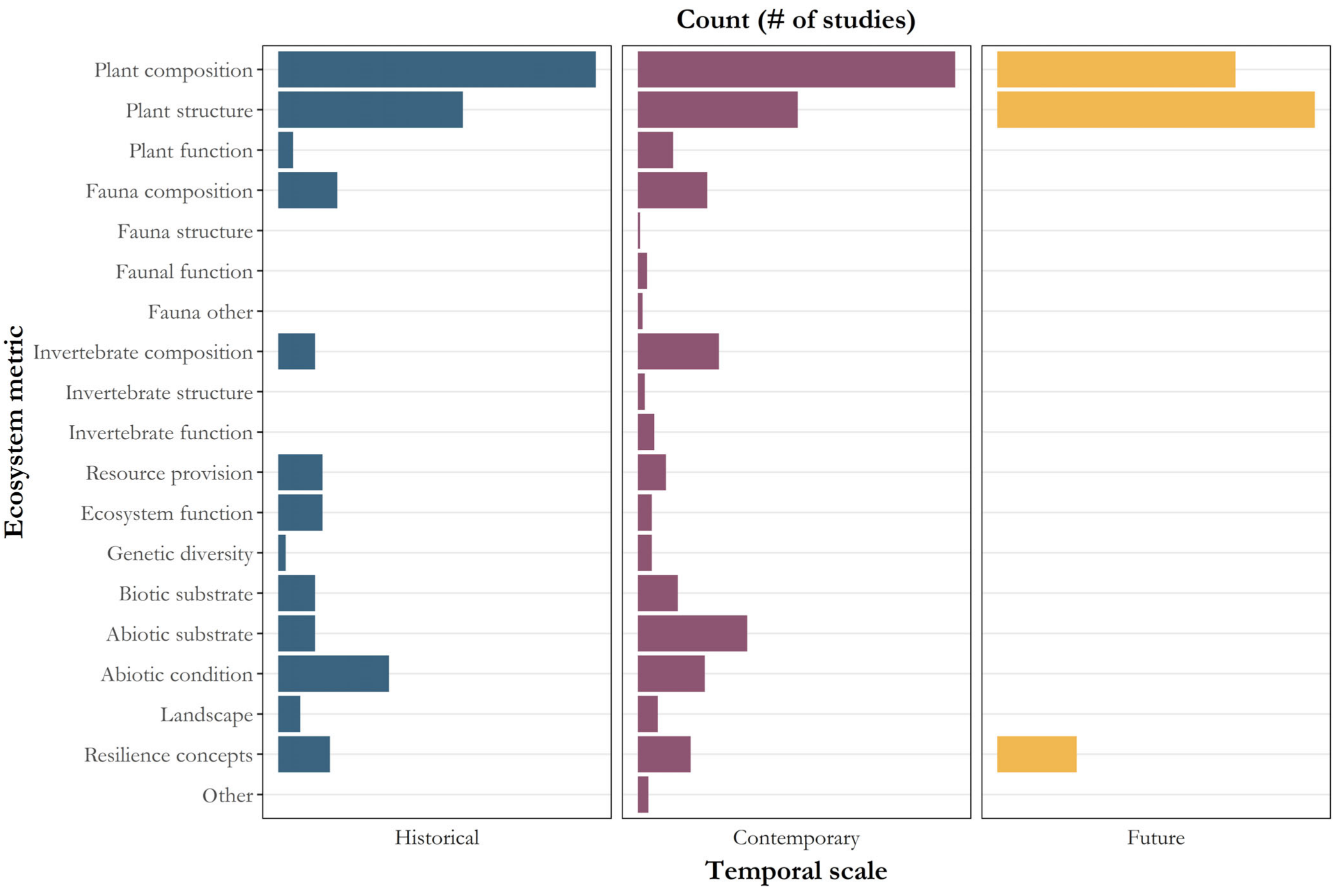

Figure 3. Common ecosystem metrics used in defining references. Bar plots illustrate the number of studies (top *x*-axis) that used the 19 classified ecosystem metrics (*y*-axis). The three panels show how these metrics were used in relationship to time, from the historical (blue), contemporary (red), and future temporal scales (yellow; bottom *x*-axis).

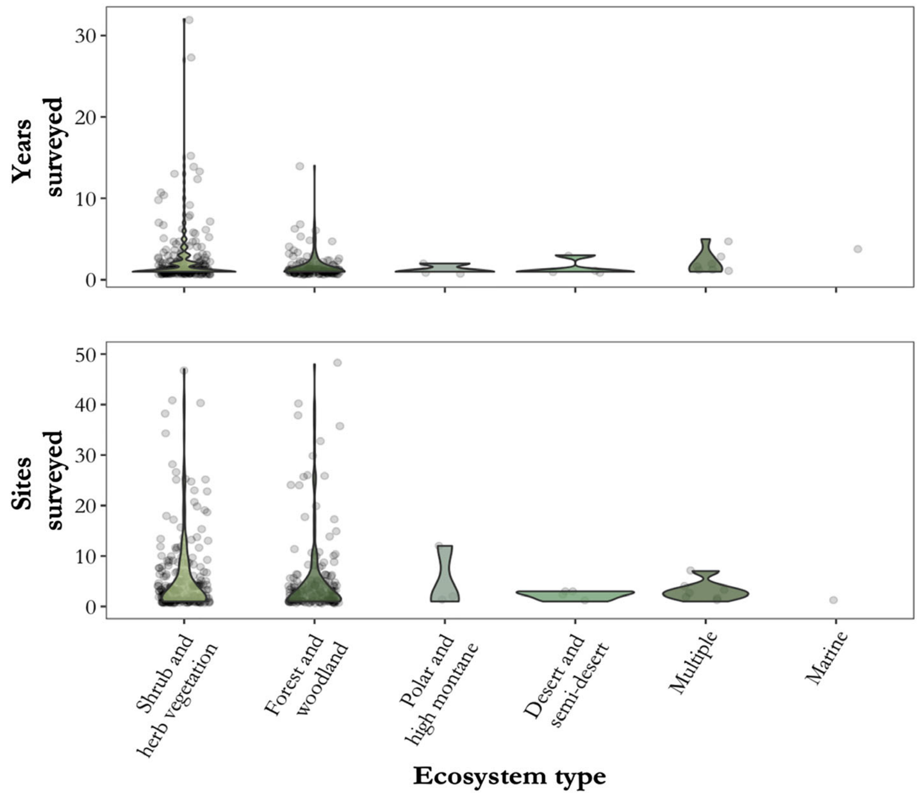

Figure 4. Sources of reference information by ecosystem type. First panel illustrates the number of years reference sites were surveyed from each study across the six ecosystem types. Second panel illustrates the number of sites surveyed for reference data within each study. Both figures use violin plots to illustrate the density and distribution of data and each gray point represents one study (i.e. one paper from the literature review), with outliers not shown.

reference concept in restoration and should be critically assessed as the field continues to grow.

Despite recommendations to use reference communities to set restoration targets, the published literature provides few examples of references that are measured and described prior to restoration actions (e.g. Suganuma et al. 2013; Celentano et al. 2014; Vélez-Martín et al. 2018). Though this may be driven by the lack of treatment effects to report prior to restoration actions, we also found few post-restoration studies that mentioned quantifying, or even assessing, references prior to the project commencement, suggesting that pre-restoration reference measurements may be less common in restoration on-ground as well as in the more science-focused literature. The importance of using references as planning tools has consistently been reinforced in recommended standards of practice (SER 2004; Balaguer et al. 2014; Gann et al. 2019). Though there may be many examples in management literature globally, internationally published scientific literature is more highly organized and accessible to wide audiences than ‘gray’ literature (Haddaway 2015; Haddaway & Bayliss 2015). Thus, having published examples of references defined prior to restoration implementation, and used for restoration design, will be key to collaboratively advancing the reference concept in this role.

The focus on benchmarking outcomes also corresponded with a heavy reliance on spatial analogs—contemporary reference data that are collected in less degraded sites characterized by a target ecosystem. In our review, 92% of the studies used data from contemporary, ecosystem-specific sources, and only 11% used multiple data sources. Contemporary data offer obvious benefits and drawbacks. Our review shows that it can provide greater diversity in the metrics considered, allowing faunal, functional, and resilience-based metrics to be assessed in addition to common metrics around plant communities. However, the temporal and spatial scale of sampling was often limited. Though natural variation is recognized as a widespread ecological phenomenon (Higgs et al. 2018) and can occur both spatially and temporally (Mori 2011), few of the studies recorded data for longer than 2 years or over more than two sites. This may lead to a narrow view of restoration targets and success and may prevent understanding certain essential ecosystem dynamics and potential transitions.

Existing data and networks can be used to extend the scope of collected data. For example, the proposed coast-wide Reference Monitoring System in Louisiana, USA, covered all major wetland types across the whole Louisiana coast. At least 200 sites were recommended for annual sampling to capture temporal variation and trends (Steyer et al. 2003), and results were recommended for use in evaluating restoration projects created based on recent state legislation. This is likely not a readily available option for many projects, however, given time and resource constraints, which likely limit the temporal and spatial scales that can be covered by field surveys. This reinforces the need to combine ecosystem-specific, contemporary reference data sources with other potential data sources.

Extensions of these temporal and spatial axes were apparent in a number of studies. Temporally, reference information was projected beyond current data through tools, such as predictive models built on climate and range distributions, or statistical predictions based on existing patterns of ecosystem occurrence in the landscape (e.g. Gibbons et al. 2008). Spatially, several studies moved beyond ecosystem-specific information and considered metrics such as naturalness (e.g. Sengl et al. 2017); floristic quality, which indicates both origin of a species and fidelity to a particular habitat or tolerance to disturbance (e.g. Wilson et al. 2013); and habitat indicator levels (e.g. Brewer & Menzel 2009). These metrics depend on species-level attributes such as disturbance preference (ruderal species to late succession), habitat preference (shade to open canopy, for example), and level of conservation concern (abundant to rare). Though this information may be a challenge to gather for individual species, there is often regionally available data (e.g. Borhidi 1995; Brudvig & Mabry 2008). In some instances (e.g. Sengl et al. 2017), these metrics have given results comparable to measures of similarity between restored and reference communities, implying that they may aim toward similar targets of traditionally defined restoration without depending on the presence of intact and well-understood reference communities.

The concept of the reference has undergone many changes, from its first mention as a set of "desired components," to being defined as a "historic indigenous community," to expanding to include human dimensions and future projections of change. The most modern concept of the reference is relatively flexible and diverse (Gann et al. 2019), and the suggested attributes to consider include lifeform types, abiotic conditions, and social components (Palmer et al. 2016). Despite this conceptual development, the realized measurement of references in the scientific literature was relatively uniform. The focus on contemporary, less degraded references is concerning given that (1) widespread degradation has resulted in many ecosystems that currently lack a contemporary analog; (2) global changes are likely causing current and future transitions in ecosystems globally; and,(3) limited sampling sizes leads to constricted definitions of acceptable outcomes. We suggest that measurements and implementation of restoration references should strive for the open flexibility encouraged by conceptual developments around the reference and its definition. Considering all potential reference data sources and their relevance to individual projects will be a key first step.

Recommendations for Best Practice

(1) *Justify the rationale for using the reference concept prior to starting a project*, as different decisions and applications will result. Are we interested in benchmarks or goal setting? When references are used to set restoration goals, we need more reporting of the data gathered and how it was used to shape restoration decision-making, even if it is embedded in studies on post-restoration outcomes.

(2) *Use multiple types of reference data* (at different scales and different times). By drawing on multiple sources, such as combining ecosystem data from contemporary sources with future projections, practitioners may prioritize contemporary ecosystem types while giving them the ability to adaptively change and track conditions into the future.

(3) *Incorporate the natural expected variability over time and space* in applying the reference concept—even an adjacent site is likely to exhibit spatial and temporal variation. Particularly in ecosystems that change over small temporal and spatial scales, such as predominantly herbaceous systems, more points in space and time will be important to defining an appropriately variable range of potential targets.

(4) *Understand the past and projected trajectories of environmental change* to inform what concept will be most applicable. Altered species pools due to the influx of exotic species, directional changes in climate or nutrients, or fundamental abiotic shifts in conditions like hydrology or landscape context will make some references impossible to achieve without sustained, costly investment (e.g. a historical references in a changing climate). Though the investment may be warranted in some instances (usually for a culturally significant element like Yosemite Valley), there should be deliberate, informed agreement on the short- and long-term implications of the reference choice.

(5) *Where appropriate, differentiate between the reference as ideal and reference as target* to manage feasibility and resource constraints. Recommendations around reference models often have expansive lists of key attributes that characterize the reference as a holistic target of restoration (e.g. Shackelford et al. 2013; McDonald et al. 2016). This runs the risk of setting standards that are unachievable by practitioners facing deeply degraded ecosystems, socio-cultural barriers, and time and resource constraints. Pinpointing individual targets within the reference model may be more feasible for practitioners and may allow more fulsome consideration of potential reference data sources across the spatio-temporal axes.

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Supporting Information

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

Supplement S1. Additional literature review details and outcomes.

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