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Review

Indicators of vegetation development in restored wetlands

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ABSTRACT

Significant wetland losses across the globe have motivated large-scale restoration efforts to improve the quality of wetland habitats. However, previous studies have shown a high variability in the outcomes of restoration treatments. Post-restoration monitoring is critical to identifying factors constraining wetland recovery and diverting sites away from restoration goals but is often limited by a lack of funding. To circumvent limitations to the large-scale monitoring of wetlands, it is pivotal to identify metrics that can be implemented at low cost yet provide a reliable signal of restoration progress. We review scientific literature on methods to appraise post-restoration progress in wetland ecosystems, focusing on vegetation-based indicators. We present a synthesis of demonstrated relationships between these indicators, site conditions, landscape context, and key ecosystem functions to highlight benefits and potential limitations to the widespread applications of these indicators to post-restoration monitoring. Based on this literature synthesis, we suggest adopting a multi-metric approach to fully measure ecosystem recovery. Potential solutions identified in this review to reduce costs associated with large-scale monitoring include: identifying correlation among indicators, focusing on the most widespread species, and using remote sensing to expand the spatiotemporal scope of monitoring and inform monitoring efforts.

1. Introduction

Wetlands play a key role in supporting biological diversity and providing ecosystem services, but have been critically impacted by global land conversions and increasing ecosystem stress (Allan et al., 2013; Costanza et al., 1997; Zedler, 2003). In response, various organizations, from local to nationwide, have initiated large-scale restoration efforts to rehabilitate depleted ecosystem functions and increase the quality and extent of wetland habitats (Bedford, 1999; Moreno-Mateos et al., 2015; Suding, 2011). The Society for Ecological Restoration defines ecological restoration as the assisted recovery of an ecosystem towards a desired state or ecological condition (SER, 2004). In wetland ecosystems, restoration interventions can include removing non-native species, planting to accelerate recovery, grading to create topographic heterogeneity, and site breeching to increase tidal prism (Simenstad et al., 2006; Zhao et al., 2016). Common goals of wetland restoration projects include extending the quality and extent of wetland habitats, restoring ecosystem services, or promoting the resilience of local communities to climatic changes and sea level rise (Kentula, 2000; Simenstad et al., 2006). Yet, recent studies have revealed a substantial variability in restoration outcomes, even among similar habitat types and restoration treatments (e.g., Berkowitz, 2013; Matthews et al., 2009), with projects sometimes falling short of restoration targets (Brudvig et al., 2017; Van den Bosch and Matthews, 2017). As a result, it is challenging for project managers to predict the outcomes of restoration treatments or identify factors that could divert their sites away from targets (Suding, 2011).

Without a consistent monitoring, it becomes difficult to identify the site characteristics, landscape factors, or management decisions that impact the post-restoration trajectory of sites (Brudvig et al., 2017). For example, hydrological connectivity between wetlands and adjacent land covers through surface flows, runoff, and groundwater can facilitate the transport of pollutants, nutrients, or non-native species (Baldwin, 2004; Moreno-Mateos et al., 2008), increasing the potential for unexpected changes and chaotic fluctuations in post-restoration trajectories. Furthermore, the need to account for variability in climatic, hydrologic, and anthropogenic factors affecting site properties can make post-restoration monitoring and site planning even more challenging (Wilcox et al., 2002; Xiong et al., 2003). Generating long-term and geographically comprehensive ecological datasets from existing sites could improve the planning and design of future projects and help managers identify the most appropriate spatiotemporal scale for post-restoration monitoring (Brudvig, 2011; Kentula, 2000; Suding, 2011). However, such a rigorous documentation of post-restoration

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Table 1
Vegetation indicators reviewed in this study, with appreciation of their predictability, ease of monitoring and interpretation.

Type	Indicator	Methods	Ease of Monitoring	Ease of Analysis/Interpretation	Predictability
Structural	**Plant coverage**: proportion of the ground covered by vegetation.	Estimation using cover classes (e.g., Braun-Blanquet); digital photography and analysis; remote sensing.	**Rapid**; can be conducted through rapid visual assessments or photography analysis.	**Easy**; can be compared to reference sites, baseline data, or previous years of data.	Responds rapidly to restoration treatments but can stabilize quickly or decline over time (Matthews, 2015; Raab and Bayley, 2012; Staszak and Armitage, 2013).
	Plant biomass: total mass of vegetation within a given area.	Direct methods (harvesting and weighing of plant biomass).	**Difficult**; direct monitoring is time consuming and potentially disruptive.	**Easy**; can be compared to reference sites, baseline data, or previous years of data.	Rapid response to environmental stressors and restoration treatments (Mollard et al., 2013; Raab and Bayley, 2012); important year-to-year fluctuations in response to abiotic and climatic variability (Anderson et al., 2016; Wilcox et al., 2002; Zedler and Langis, 1991).
		Indirect methods (leaf area index, allometric equations, analysis of remotely sensed data).	**Difficult**; presence of standing litter may affect indirect measurements.	**Variable;** correction factors specific to individual species or functional groups may be needed to account for the effect of litter and water level.	Rapid response to environmental stressors (Mollard et al., 2013; Raab and Bayley, 2012).
Species composition	**Species richness:** number of species in a plot of site.	Species identification.	**Moderate to difficult**; requires experts or well-trained personnel to identify species; risk of overlooking rare species if area monitored is too small.	**Easy to moderate;** can be compared to reference sites, baseline data, or previous years of data.	Some studies have shown increases over time (Gonzalez et al., 2014), but other observed later declines as a result of biological invasions (Yepsen et al., 2014). Sites can recover slowly (Galatowitsch and Van der Valk, 1996; Moreno-Mateos et al., 2012).
	Species evenness: distribution of abundances within an ecological community.	Species identification along with assessment of abundance through stem count or coverage estimation.	**Moderate to difficult;** requires experts or well-trained personnel to identify species; risk of overlooking rare species if area monitored is too small.	**Easy to moderate;** can be compared to reference sites, baseline data, or previous years of data.	Sensitive to biological invasions (Yepsen et al., 2014).
	Species diversity: number of species present and the relative abundance of individuals per species.	Species identification along with assessment of abundance through stem count or coverage estimation.	**Difficult;** sensitive to sampling size and taxonomic knowledge.	**Easy to moderate;** can be compared to reference sites, baseline data, or previous years of data.	Responds to landscape context, management, and local environmental conditions (Bernhardt and Koch, 2003; Galatowitsch and Van der Valk, 1996; Seabloom and van der Valk, 2003), but shows variable response time to restoration treatments (Matthews and Spyreas, 2010; Moreno-Mateos et al., 2012).
	Coefficient of conservatism: expert-based ranking of species from highly tolerant species (score of 0) to specialized species (score of 10).	Species identification.	**Moderate**; little sensitivity to sampling size (complete sampling size not required); requires capacity to accurately identify species.	**Moderate to difficult**; requires pre-established ranking of species; variable results where two jurisdictions are overlapping; biased where new species (not yet ranked) are occurring.	Sensitivity to landscape composition, site conditions, and restoration treatments (Bourdaghs et al., 2006; Matthews, 2015).
	Floristic quality index: calculated by multiplying the mean coefficient of conservatism of a given plot or site by the square root of its species richness.	Species identification.	**Moderate to difficult**; requires complete site inventory or well-established species-area curves; requires capacity to accurately identify species.	**Moderate to difficult**; requires pre-established ranking of species; variable results where two jurisdictions are overlapping; biased where new species (not yet ranked) are occurring.	Significant variation with species composition (e.g., richness, diversity, evenness) and site characteristics (age, soil chemical composition) (DeBerry and Perry, 2015) and landscape context (Lopez and Fennessy, 2002).
	Indicator species analysis: subset of species representative of habitat characteristics, site conditions, or plant community type.	Identification of indicator species, and in most case, measurement of their abundance.	**Easy to moderate**; simplifies species composition assessment by focusing on a small set of species.	**Moderate to difficult**; requires initial sampling across many sites and species to identify the species most responsive to specific conditions or habitat types.	Sensitive to site conditions (Gonzalez et al., 2014).

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