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SPECIAL ISSUE: CONCEPTS AND CONTROVERSIES IN TIDAL MARSH ECOLOGY REVISITED

Tidal Marsh Restoration Optimism in a Changing Climate and Urbanizing Seascape

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Abstract
Tidal marshes (including saltmarshes) provide remarkable value for many social (cultural, recreational) and environmental (fish production, water quality, shoreline protection, carbon sequestration) services. However, their extent, condition, and capacity to support these services are threatened by human development expansion, invasive species, erosion, altered hydrology and connectivity, and climate change. The past two decades have seen a shift toward working with managers to restore tidal marshes to conserve existing patches or create new marshes. The present perspective examines key features of recent tidal marsh restoration projects. Although optimism about restoration is building, not all marshes are the same; site-specific nuances require careful consideration, and thus, standard restoration designs are not possible. Restoration projects are effectively experiments, requiring clear goals, monitoring and evaluation, and adaptive management practices. Restoration is expensive; however, payment schemes for ecosystem services derived from restoration offer new ways to fund projects and appropriate monitoring and evaluation programs. All information generated by restoration needs to be published and easily accessible, especially failed attempts, to equip practitioners and scientists with actionable knowledge for future efforts. We advocate the need for a network of tidal marsh scientists, managers, and practitioners to share and disseminate new observations and knowledge. Such a network will help augment our capacity to restore tidal marsh, but also valuable coastal ecosystems more broadly.

Keywords Restoration challenges · Restoration knowledge · Restoration opportunities · Saltmarsh · Seascape

Introduction

Tidal marshes (including saltmarshes) are located along the landward margin of estuaries and bays, and hold remarkable natural value (e.g., Zimmerman et al. 2000; Anderson and Smith 2014; Baker et al. 2020; Weinstein et al. 2021). Despite recognition of these services, human activities continue to modify tidal marsh extent and quality through urban and industrial expansion (Boyes and Elliott 2006; Melville et al. 2016), grazing by livestock (Davidson et al. 2017; Harvey et al. 2019), and altered hydrology (Spencer et al. 2017). Tidal marsh restoration projects have consequently emerged, increasingly in the past two decades, in an attempt to halt and reverse marsh loss (Weinstein 2007; Gedan et al. 2009; Roman and Burdick 2012; Finkl and Makowski 2017). To achieve or maintain functionality that is similar to natural marshes, restoration projects must consider seascape context and urban encroachment (Weinstein and Reed 2005; Gilby et al. this issue), changing sea level and warming temperature (Colombano et al. 2021), drivers of geographical variability (Ziegler et al. 2021), and changing social, and cultural values and perspectives (zu Ermgassen et al. this issue), all in an age of novel and emerging technological advancements (Kimball et al. this issue). Although optimism about restoration is building (Waltham et al. 2020), not all marshes are equivalent in terms of structure and function; many site-specific nuances need careful consideration (Minello 2017). For example,

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intertidal marshes vary enormously in elevation and flooding patterns among geographic locations with differing tidal regimes, e.g., USA Gulf of Mexico, North American east coast, and Australian east coast (Connolly 1999; Minello et al. 2012); thus, standard restoration design is not possible.

Two decades have passed since the meeting and subsequent compilation of papers that produced the *Concepts and Controversies in Tidal Marsh Ecology* book (Weinstein and Kreeger 2000)—a synthesis of the best available knowledge at the time for scientists and managers working in tidal marsh ecology. Since that publication, a major shift has occurred in science toward problem-solving (Dennison 2008); this shift has been observed for tidal marshes, in response to increasing pressures from climate change–related threat and sea-level rise (SLR), and continuing encroachment of urban and industrial areas. This movement has given rise to tidal marsh restoration projects and research focused on demonstrating whether such efforts are successful, and worth the investment (Weinstein et al. 2021). For the present perspective, we assess work over the past two decades to determine key considerations for tidal marsh restoration, including issues such as SLR impacts, hydrology and connectivity, integrating restoration projects into seascape thinking, the need to set goals, data requirements, and embracing new technology. This perspective is timely, particularly given the recent United Nations (UN) General Assembly declaration that 2021–2030 is the "UN Decade on Ecosystem Restoration," which calls for a halt to further coastal wetland destruction, and brings attention to the need for major restoration programs (Waltham et al. 2020). Although we recognize the distinction between tidal marsh restoration for habitat rehabilitation (i.e., work on existing tidal marshes that have become degraded or impacted) and marsh creation (i.e., resulting in newly created habitat), we treat them together in our perspective, since they have similar ultimate objectives and desired environmental outcomes.

Sea-level Rise

While SLR is the most recognizable climate change–related threat in tidal marsh seascapes causing increased erosion to shorelines, emerging evidence suggests that it could actually be advantageous for some tidal marshes. For example, while SLR changes inundation patterns causing a redistribution of marsh plants, increased inundation can lead to more marsh area becoming available for fish (Grieger et al. 2019; Abbott et al. 2020). Note that restoring the lowest, most frequently inundated marsh areas substantially improves value of the restoration, including nekton use, of the marsh as a whole. Such habitat extension, by removal of earth walls to reintroduce tidal inundation, was attempted in Australia with some success (Abbott et al. 2020). Upon reflection, addressing the threat and potential opportunities presented by SLR is best done during the planning phase, regardless of whether the objective is habitat rehabilitation or creation, to consider local site characteristics, including present and future rainfall and temperature regimes (Gabler et al. 2017). Thus, our view here is that understanding the interactive effects of climate and SLR requires careful assessment by experts to properly distinguish among sites susceptible to erosion (Kirwan and Murray 2007), and those predisposed for habitat expansion (Raabe and Stumpf 2016). Furthermore, to assist with this assessment phase, there is a need to develop a system to rank and prioritize restoration opportunities and approaches, to move beyond "opportunistic" responses, and to reduce the risk of restoration failure.

Restoring Hydrology and Connectivity

Tidal marsh hydrology and restoration success are strongly linked (Warren et al. 2002; Montalto and Steenhuis 2004; Roman and Burdick 2012). An obvious consequence of reinstating or maintaining hydrological connection, and tidal inundation, is access to the tidal marsh by nekton (Minello et al. 2003; Rozas and Minello 2007). Marshes provide refuge from predation, direct feeding opportunities on local food sources (Hollingsworth and Connolly 2006), and export of organic matter to the broader seascape food webs (Kneib 1997; Jinks et al. 2020). Such marsh access has measurable fishery benefits, even though frequency and duration of tidal flooding, and resultant access, varies markedly geographically (Thomas and Connolly 2001).

Other consequences of reinstating tidal inundation include increased accretion rates from suspended sediments, which promotes resilience against SLR—via vertical and horizontal expansion of the marsh (Windham-Myers et al. 2013; Beauchard et al. 2014; Oosterlee et al. 2018), as well as carbon sequestration benefits (Artigas et al. 2015).

Sediments may accumulate naturally where hydrology has been restored (e.g., Virgin et al. 2020) or be used purposely for marsh restoration or creation (e.g., Staver et al. 2020). With regard to the latter, the deposition of fine-grain dredged sediments seems to be more conducive to plant growth than upland or dredged sandy sediments, both of which can have relatively low nutrient content (Sparks et al. 2015). Generally, abiotic and biotic soil-related characteristics, such as nutrient content, temperature and moisture, and rhizosphere microbial community, influence restoration success (Diefenderfer et al. 2018; Mavrodi et al. 2018; Sloey and Hester 2018; Staver et al. 2020). The supply of marine and riverine sediment and the implications for geomorphological processes are discussed further in Ziegler et al. (2021) and Able (this issue).

Upon reinstating tidal inundation to restore marshes, attention must also be given to invasive species, and limiting establishment or spread and competition with native species (Clifton et al. 2018). A well-documented example is *Phragmites australis* monocultures in the USA, which level the marsh surface, reduce topographical heterogeneity, and hinder recovery by native plant species and of the marsh as a whole (Weinstein and Balletto 1999; Weinstein et al. 2000). Based on evidence to date, restoration areas that experience the most rapid vegetation recovery are planted with local marsh species and have appropriate elevations, hydrological connections, and soil water tables that boost plant growth (Minello and Zimmerman 1992; Warren et al. 2002).

Applying Seascape Context to Tidal Marsh Restoration

Tidal marshes occur in a seascape, along with other types of biogenic habitat (e.g., coral reefs, mangroves, seagrass, beaches, and oyster reefs), and their position in this broader spatial context can influence their function for fauna and services such as sediment stabilization, water quality enhancement, and carbon sequestration (Grabowski et al. 2005; Gilby et al. 2018). Restoration of other nearby habitats can enhance plant and faunal communities in tidal marshes over time. For instance, more than 10 years after oyster reef restoration in North Carolina, USA, local sediments had stabilized and allowed the expansion of an adjacent tidal marsh (Ziegler et al. 2018). Moreover, marsh geomorphology can affect the overall success of adjacent oyster reef restoration, including habitat utilization by nekton (Keller et al. 2019). However, the restoration of other habitat types near to marshes, and vice versa, may result in functional redundancy, and not increase, for example, nekton aggregation or production (Geraldi et al. 2009); this is a topic that requires more study.

An interesting and potentially related aspect is that if restored subtidal reefs are not sufficiently close to the shoreline, they may not be effective at securing or enhancing the persistence of restored tidal marshes (Scyphers et al. 2011; Moody et al. 2013). In contrast, intertidal reefs placed adjacent to restored marshes can promote the expansion and resilience of marshes (Sharma et al. 2016a). Typically, as the distance from the reef to the marsh increases, and the reef shifts from intertidal to subtidal, the protective effect of the reef on the marsh decreases (Fig. 1), making the use of reefs for coastal protection purposes challenging (Sharma et al. 2016b; Morris et al. 2019).

Marsh restoration projects often focus on the protection of habitat edges, by using channels with appropriate size distributions or other geomorphological features (Jin et al. 2014; Hood 2018; Heuner et al. 2019), or even artificial structures. Examples of the latter include strategic placement of artificial oyster reefs, to dissipate wave energy, and the addition of

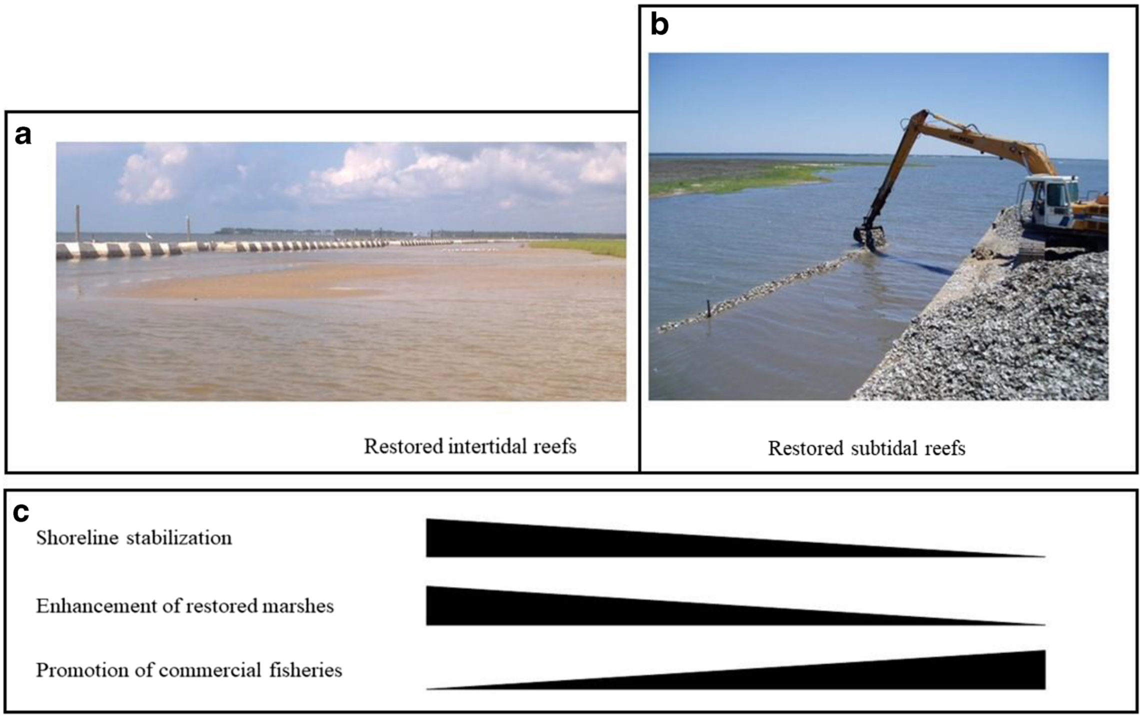

Fig. 1 Example of **a** intertidal and **b** subtidal restored reef (see Sharma et al. 2016a and Sharma et al. 2016b, respectively, for more details; photos courtesy of those authors). The reefs provide shoreline protection from wave energy during severe weather, and the opportunity for vegetation to colonize in the created sheltered waters. **c** Typical gradients in shoreline stabilization, enhancement of restored marshes, and promotion of commercial fisheries found among reef types; the right triangles represent relative effectiveness seaward from intertidal to subtidal reefs

living shoreline components, such as marsh sills or breakwaters, to protect marsh edges and enhance biodiversity and productivity (Beck et al. 2011; zu Ermgassen et al. 2016). Some of the most successful marsh restoration projects are large areas of low marsh interspersed with dense networks of shallow channels and interconnected ponds, with topographic heterogeneity and appropriate elevation (Rozas and Zimmerman 2000). In this way, marsh creation that replaces open water has successfully extended marsh habitat for nekton (Rozas and Minello 2007; Silver et al. 2017).

Recent projects have been designed to integrate marsh restoration into urban seascapes (see Fig. 2a). Living shorelines use a variety of hybrid "eco"-engineering techniques (Bilkovic et al. 2016) to decrease erosion and increase catch rates of nekton (Gittman et al. 2016a). The application of living shorelines to balance urban sprawl with habitat protection has become a popular research area, and an exciting nexus of expertise from engineers, ecologists, landscape architects, marine contractors, property owners, outreach, and education staff. Despite the broad appeal, barriers to large-scale implementation remain (Stewart-Sinclair et al. 2020). These barriers include limited comparability between projects and research results (Gittman et al. 2016b), access to experienced marine contractors, difficulties in obtaining permits, inadequate marketing, lack of cost share or incentive programs for private property owners, limited technical assistance and education programs, and overcoming public perceptions that hardened structures are superior to living shorelines for property protection. For living shoreline practices to become mainstream in tidal marsh restoration, collaboration and multidisciplinary research, education, and training are critically needed (Rezek et al. 2017).

Setting Realistic Restoration Goals

Setting realistic goals and objectives is an obvious and straightforward prerequisite for tidal marsh restoration (Weinstein et al. 1997; Ehrenfeld 2000; Prach et al. 2019), but this is sometimes overlooked or poorly defined during project inception. Establishing them can be missed in the fray to secure funding and convince stakeholders of the importance of a restoration project. Without clear and realistic objectives, it is difficult to learn and improve practices beyond the realm of optimism. Furthermore, defining "restored," establishing baselines or reference conditions, balancing legal, funding and agency objectives, being pragmatic and cost-effective, as well as optimizing multiple and competing outcomes, are all challenges that restoration practitioners face when working to demonstrate the financial and broader sustainability of projects.

In a time of many ecosystem threats and environmental stressors, the need for multiple use (bundled) outcomes for restoration has become overwhelming (Paschke et al. 2019). Funding schemes often have different mandates and need to justify distinct targets, which can make restoration planning complicated. A currently common example is trying to balance the goal of creating high-quality habitat for fisheries production, which requires low-elevation marsh, and the goal of increasing

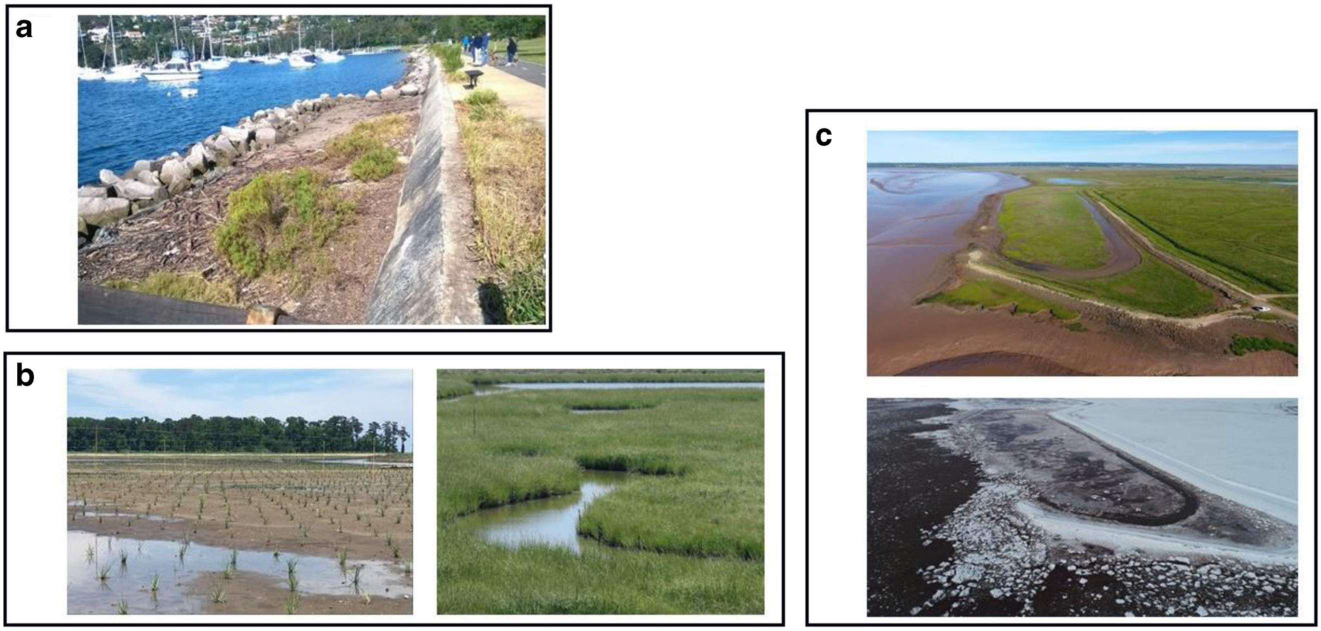

Fig. 2 Tidal marsh restoration examples: **a** assisted saltmarsh recolonization using a purposely engineered benched platform along a seawall, Sydney, Australia (photo courtesy of Dr. R. Coles); **b** tidal marsh restoration planting (*left*) and mature marsh (*right*) at the Paul S. Sarbanes Ecosystem Restoration Project at Poplar Island, Maryland, USA (photos courtesy of Dr. L. Staver); and **c** saltmarsh restoration, in summer (*top*, July 2017) and winter with ice cover (*lower panel*, February 2020) in the Bay of Fundy, Aulac, New Brunswick, Canada (photos courtesy of Dr. M. Barbeau and Clean Foundation Nova Scotia)

shoreline protection, which works best with high-elevation marsh. Balancing decisions on multiple-use trade-offs can be slow and expensive. Currently, no standard tools exist that help practitioners make optimized decisions in the face of competing objectives (Gilby et al. 2020). Development of a toolbox to centralize and disseminate data and information to restoration practitioners would be very useful.

Restoration Projects as Experiments, and Adaptive Management

Habitat restoration is inherently risky and subject to substantial uncertainty (Lee et al. 2019). The current extent and rate of degradation of coastal ecosystems necessitate big and bold approaches to restoration (Jiang et al. 2015). Yet, there are substantial gaps in our knowledge of how tidal marsh plants respond to sub-optimal conditions, such as increased amount of nutrients. Even if a marsh is cleansed of legacy effects and environmental conditions are again favorable, how the restored marshes will fare with accelerated SLR is uncertain.

One way to close the knowledge gap is through monitoring and experimentation in current tidal marsh conservation and restoration efforts. Funding is often not available over the medium and long term for monitoring marsh restoration, including living shorelines and thin layer placement sites (i.e., purposeful placement of sediment or dredged material), but it is critical to learn about the effectiveness of implementation strategies, both at present and as SLR accelerates in the future. Experiments embedded in restoration projects (Silliman et al. 2015; Gellie et al. 2018) can help develop insights and obtain data to calibrate models of marsh response to SLR, inform long-term restoration projects (e.g., Poplar Island; see Fig. 2b) and adaptive management strategies, and provide examples for improved future design.

Well-funded cross-disciplinary research programs will enhance the capacity to achieve successful restoration of tidal marshes in a changing world. However, even with the best research and support available, success targets still have inherent risk and uncertainty. Even setting optimistic objectives when the steps toward accomplishing such targets are well understood is challenging, as future conditions for the project cannot be predicted with certainty (Sutton-Grier et al. 2015). Restoration ecology is not an exact science and intrinsically relies on probabilities of outcomes and adaptive management.

Given uncertainties and to maximize success, it is important to adopt an adaptive management framework, whereby a restoration project is continuously monitored and its design, execution, implementation, and further monitoring amended as warranted by unexpectedly changing conditions and inherent uncertainty in the initial plan (Teal and Weishar 2005). Along with continuous monitoring (with the time period ideally determined by the life histories of the species and the restoration targets involved) the application of adaptive management requires knowledge of effective, fast-action corrective measures, which can be identified and validated with research programs—leading to new research hypotheses. Thus, monitoring, experiments, and adaptive management all have their separate and complementary roles in restoration projects.

It is also important to note that project proponents may take literature or studies from a given context and apply the same to their location, without understanding site constraints, context, and applicability (see also Ziegler et al. 2021). In our experience, this is a real danger for restoration success. For example, researchers working on a tidal marsh restoration project in the upper Bay of Fundy (Fig. 2c) discovered this when designing their restoration plans and consulting available literature, which was available for case studies in other geographic locations with very different local conditions (Boone et al. 2017; Virgin et al. 2020). It is also difficult to account for every variable when designing and implementing a restoration project. In all such cases, it is necessary to apply monitoring and implementation of new research components (adaptive research).

Acquiring, Reporting, and Archiving Restoration Data

As the number and scale of restoration projects increase, so will the need to access and share knowledge gained. Systematic reviews, assessments of needs derived from engagement with restoration practitioners, and peer-reviewed literature documenting restoration monitoring and interpreting results, concept, and designs are among the most important information needed to further restoration science (Bayraktarov et al. 2016). However, efforts to meaningfully synthesize information at the regional scale, where it may be of most value to practitioners, have been hampered by a lack of standardized monitoring protocols and data reporting (McKinley et al. 2020).

Advancements in the application and access to technological and machine learning capability have occurred in the past few decades, which has revolutionized how we engage in environmental data collection and knowledge transfer (Kimball et al. this issue). For example, advancements in sonar video techniques provide an unprecedented ability to collect masses of management-relevant data (Lankowicz et al. 2020). Access to remote sensing data now means that global ecosystem mapping datasets are being generated to assess the extent and rate of change (Murray et al. 2019). Advancements in the use of unmanned aerial vehicles (UAVs) to monitor elevation and change using structure-from-motion technology are now available, which may reduce monitoring costs and increase opportunities (Kalacska et al. 2017). Access to affordable environmental sensors has quickly become a best-practice necessity, also creating new opportunities for big data analyses and data visualization (Temple et al. 2020; Zhang et al. 2017; Kimball et al. this issue). Further technological developments will continue to enhance data collection and transfer into actionable knowledge, which will be particularly useful in evaluating and validating restoration success. All these data, including project failures, should be made available in peer-reviewed literature.

Developing a consistent framework of open reporting and archiving of restoration and monitoring data would substantially expand the knowledge base and improve our ability to identify successful strategies, and avoid unsuccessful outcomes and repeated mistakes. Numerous such reports exist as gray literature and those that do are difficult to access in government departments or consulting agencies. Permitting agencies are best positioned to record, compile, and disseminate the latest knowledge in restoration design and learning, and we should give thought to this in developing a data reporting and archival system. As mentioned above, however, there is currently a lack of standardization in restoration monitoring and data reporting formats; this is in part due to the broad range of methods, goals, and environmental contexts of restoration projects, and perhaps also to limited funding (Gellie et al. 2018). At a minimum, reports should include a detailed account of all work done, including a quantitative description of activities and specific techniques employed for each restoration feature (i.e., location distinguished spatially and/or by restoration activity), such as fill and excavation volume, number and density of plantings, areal coverage, targeted elevation, and number and species of removed invasive species. Reports should include a map(s) identifying all aspects of restoration and monitoring activities, including the areal footprint of all features, reference sites, monitoring stations, and all other locations relevant to the project (e.g., plant donor sites, disturbance locations). It would be useful to state the itemized cost of all construction and monitoring activities to provide a means of cost-benefit comparisons among different restoration approaches (Bayraktarov et al. 2016). As well, project reports should outline all relevant information related to the environmental context of the system (e.g., salinity range, tidal range, landscape characteristics), and identify specific disturbances that have led to habitat degradation and the motivation for restoration (Waltham et al. 2020). Including these details would, hopefully, improve the success of future projects.

Recommendations—the Next Generation of Tidal Marsh Restoration

While interest in restoration for tidal marsh rehabilitation and creation increases, we detect the emergence of a degree of optimism, that marsh restoration will be at a sufficient scale, assuming that sufficient resources are allocated, and quality to closely resemble critical function and services provided by natural marsh habitat. We recommend that restoration projects be effectively considered experiments, and therefore have clear design goals and monitoring protocols, to collect robust data to evaluate restoration dynamics and success. We also recommend that all information, including when a project fails, be reported in an open way, to equip practitioners and scientists with applicative knowledge. Actionable recommendations are particularly necessary given the nuances and geographic variation in tidal marsh conditions, and that one standard restoration design or approach will not be broadly suitable. Furthermore, co-production of restoration science and policy knowledge (a strategy from Jasanoff (2004) about embedding scientific knowledge in social identities, institutions, and politics) will help establish more streamlined communication and collaboration among scientists, managers, and decision-makers from the onset, and should improve restoration success (e.g., van der Molen et al. 2015).

Restoration can be expensive, and funding is usually project or site-based, short-term (1 to 5 years) and generally does not cover long-term maintenance or the science necessary for appropriate evaluation. Payments for ecosystem services derived from tidal marsh restoration, such as valuing contribution to fisheries or carbon sequestration, offer new ways of funding tidal marsh restoration projects (Herr et al. 2015; Weinstein et al. 2021). Government funding is limited and inconsistent because of competing, and reactive policy priorities. However, accessing public funding (philanthropic or corporate investment) could unlock major funding avenues, though such schemes would require quantifiable evidence of a return on investment. These monitoring and auditing expenses could become a line-item expense that is part of the business of restoration (Waltham et al. 2020), making tidal marsh restoration an encouraging case for conservation optimism.

Restoration of tidal marshes has been a major research area since the first tidal marsh symposium (Weinstein and Kreeger 2000) over two decades ago. Examples of published restoration projects exist; however, access to consolidated information to assist managers and practitioners with their local projects is limited. We advocate the need for a network of tidal marsh scientists and managers/practitioners to share and disseminate new observations and knowledge with respect to marsh restoration—examples of successful networks exist (Schollaert et al. 2019; Torres et al. 2017). Such a network would further boost our capacity to protect and enhance valuable coastal ecosystems (McKinley et al. 2020).

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