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Evaluating Restored Tidal Freshwater Wetlands

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CHAPTER

25

Evaluating Restored Tidal Freshwater Wetlands

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1. INTRODUCTION

Tidal freshwater wetlands are recognized as highly productive coastal wetlands that support diverse assemblages of plants and animals and complex biogeochemical cycles (in this book, see Chapter 18 by Whigham et al. and Chapter 19 by Megonigal and Neubauer). Many tidal freshwater wetlands and their associated ecosystem services have been damaged or destroyed by urbanization, agriculture, and other human activities (Baldwin, 2004; Barendregt et al., 2006). Increasing recognition of the value of remaining wetlands and environmental regulations requiring wetland mitigation (i.e., enhancement, creation, or restoration of wetlands to compensate for wetland losses; Kentula, 2000) has driven the restoration of all types of wetlands, including tidal freshwater wetlands. These restoration projects have been increasingly studied by restoration ecologists, with the overarching goal of improving restoration approaches.

In this chapter, we first review characteristics of restored tidal freshwater wetlands in North America and Eurasia, where most studies have been done, including their distribution, general construction methods, and motivating factors for restoration (Section 2). Then we present criteria for evaluating tidal freshwater wetland restoration projects (Section 3). Next we describe a case study of restored tidal freshwater wetlands in the Anacostia River watershed in Washington, DC, USA (Section 4). Finally, we provide conclusions and recommendations to increase the successful restoration of tidal freshwater wetlands (Section 5).

Coastal Wetlands
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2. MOTIVATION AND CONSTRUCTION METHODS FOR RESTORATION

Tidal freshwater wetlands have been restored to mitigate for wetland losses due to development (roads, buildings), stream channelization, and other hydrologic alterations and to protect shorelines, reduce flooding, control invasive species, and restore the ecosystem functions of converted wetlands (Table 25.1). In the US Pacific Northwest and the Fraser River in British Columbia, Canada, restoring habitat for salmon-dominated fisheries and wildlife has been an important motivation for the restoration of tidal freshwater wetlands (e.g., Simenstad and Thom, 1996). Extensive restoration of tidal freshwater wetlands (and more saline wetland types) in the Mississippi River delta plain in Louisiana has aimed to (1) stabilize or reverse loss of wetlands due to erosion and increasing relative sea level; (2) increase the ratio of land to open water; (3) reduce saltwater intrusion; and (4) promote the development of natural delta features (USACE, 2017). In the more densely populated mid- and southeast Atlantic US regions, restoration has been frequently implemented to mitigate for wetlands lost to urban development, including bridges and roads, or to create mitigation “banks” from which developers can draw credits to offset future losses. On the European Atlantic coast, formerly drained, diked, or “poldered” tidal freshwater wetlands have been reconverted to wetlands to protect shorelines against storms and sea level rise and to create habitat for biodiversity support (Fig. 25.1) (Beauchard et al., 2011).

Restoration of many tidal freshwater wetlands, particularly along the East Coast of the United States, involves excavation of upland soils or placement of dredged sediment in open water areas to create a substrate suitable for plant growth at an intertidal elevation similar to those of naturally or previously occurring tidal freshwater wetlands (Table 25.1; Baldwin, 2009). In locations where former wetlands were surrounded by dikes, levees, or embankments to dewater them for agriculture (forming areas termed “polders” in Europe; e.g., US Pacific and European Atlantic coasts), breaching of embankments is a common method for restoration and that sometimes occurs inadvertently when structures fail (Fig. 25.2) (Hester et al., 2016). In Europe, this approach has been termed “managed retreat,” “managed realignment,” or “de-embankment.” An emerging approach at some locations has been to restore an adequate tidal regime using “controlled reduced tide” structures (Fig. 25.3), which include a high inlet and low outlet at the connection to the estuary (Beauchard et al., 2011; Vandenbruwaene et al., 2011). In the Mississippi River delta, restoration techniques that can be used over vast areas are necessary, including diverting sediment-laden river water into deteriorating areas to increase elevation of subsided former wetlands, restoring historical hydrologic connections to tidal channels, and pumping in dredged material to increase elevation (USACE, 2017).

Most tidal freshwater wetlands projects have focused on creating wetlands dominated by herbaceous plants (“marshes”) (Fig. 25.4). However, the McIntyre Tract associated with the Cape Fear River in North Carolina has included planted trees and shrubs, as well as herbaceous plants with the goal of restoring tidal freshwater cypress-gum swamp and marsh/scrub-shrub habitat (Land Management Group, 2004). More recently, interest has increased in restoring tidal freshwater forested wetlands on the US Pacific Coast, an ecosystem type that has been little studied where large woody debris has considerable influence on hydrology and wetland development (Diefenderfer and Montgomery, 2009). In practice, if

TABLE 25.1 Examples of Motivating Factors for Restoration and Construction Methods for Tidal Freshwater Wetlands Restoration Projects

Region	Motivating Factors for Restoration	Construction Methods	References
USA Northeast Atlantic	Remove nonnative plant species	Herbicide and cutting	Findlay et al. (2003), Meyerson et al. (1999)
USA Mid-Atlantic	Mitigate road, airport, bridge construction losses; channel maintenance and dredge material disposal; ecosystem and habitat restoration; restoration of submersed aquatic vegetation	Excavation of uplands; raising elevation with dredged sediment; cutting tidal channels; control invasive plants; reestablish tidal exchange with channels or automated tide gates; planting, seeding, transplanting of submersed plants	Kaminsky and Scelsi (1986), Bartoldus and Heliotis (1989), Bartoldus (1990), Bowers (1995), Syphax and Hammerschlag (1995), Marble and Company (1998), Baldwin and DeRico (1999), Gannett Fleming (2001), Quigley (2001), Verhoeven et al. (2001), Neff (2002), Leck (2003), Neff and Baldwin (2005), Hammerschlag et al. (2006), Neff et al. (2009), Moore et al. (2010), Prasse et al. (2015), DNREC (2016)
USA Southeast Atlantic	Mitigate road construction impacts; restoration for mitigation banking to offset losses	Grading, recontouring, cutting tidal channels, breaching berm along river, removing pump structures	Land Management Group (2004), Hopfensperger et al. (2014)
USA Pacific: Sacramento—San Joaquin Delta, California	Ecosystem restoration	Breach levees surrounding delta islands (similar to "Managed Realignment" used in Europe); excavation to reduce elevation; unrepairable levee failure	Simenstad et al. (2000), Orr et al. (2003), Stillwater Environmental Services (2003), Phillip (2005), Lehman et al. (2010), Whitley and Bollens (2014), Sloey et al. (2015), Hester et al. (2016)
USA Pacific Northwest	Mitigation for development; ecosystem restoration; fisheries habitat restoration	Levee breaching; dike removal; culvert reconnection to estuary; excavation of fill material	Simenstad and Thom (1996), Gray et al. (2002), Tanner et al. (2002), Diefenderfer and Montgomery (2009), David et al. (2014)
USA Gulf of Mexico: Louisiana	Reduce marsh erosion and inundation; reduce salinity; increase land—water ratio; promote natural delta development; fish and wildlife habitat	Hydrologic restoration; shoreline protection; freshwater diversion; dredge material placement; marsh "terraces" to promote sedimentation and reduce erosion of restored wetlands	Lane et al. (1999), Sullivan (2015), USACE (2017)
Canada: Fraser River, British Columbia	Ecosystem restoration for fisheries	Dredge spoil placement; transplanting of vegetation plugs to barren sites	Kistritz (1996), Levings and Nishimura (1996, 1997), Grout et al. (1997)

Continued

TABLE 25.1 Examples of Motivating Factors for Restoration and Construction Methods for Tidal Freshwater Wetlands Restoration Projects—cont'd

Region	Motivating Factors for Restoration	Construction Methods	References
Europe: Various estuaries	Protect shorelines against storms and sea level rise; increase area of coastal wetlands; moderate the "coastal squeeze"	Managed realignment: restoring tidal hydrology to formerly reclaimed land by breaching or removing dikes; "managed retreat; "depoldering"	French (2006)
Europe: Scheldt estuary, Belgium	Flood protection and ecosystem restoration	Controlled reduced tide system to create suitable tidal regimes in managed realignment projects; high inlet and low outlet connection to tidal estuary	Cox et al. (2006), Jacobs et al. (2009), Beauchard et al. (2011, 2013b), Vandenbruwaene et al. (2011, 2012)
China; Yellow River Delta	Restore native plants (including *Phragmites australis*), wildlife, and other wetland functions	Diversion of fresh river water into salinized wetlands to reverse saltwater intrusion cause by dam construction	Wang et al. (2012)

site conditions allow, it may be beneficial from a habitat complexity perspective to create a mosaic of multiple habitats within tidal freshwater wetland restoration projects, including submersed, floating-leaved, and emergent herbaceous vegetation, shrub- or tree-dominated stands, open water, and unvegetated mudflat areas.

Information is lacking on tidal freshwater wetland restoration from many parts of the world, although it appears to be increasing. For example, China began restoring wetlands in 1990 and is dedicating over $100 billion (USD) for coastal and inland wetland restoration by 2030 (Zhao et al., 2016). Some of these are tidal freshwater wetlands (Wang et al., 2012).

3. EVALUATION CRITERIA FOR RESTORED TIDAL FRESHWATER WETLANDS

Despite the difficulties of defining success, several reviews have indicated that wetland restoration projects often do not attain conditions that can be deemed legally or ecologically successful (Mitsch and Wilson, 1996; Zedler and Callaway, 1999; Craft et al., 2003; Baldwin et al., 2009; Suding, 2011). Limited restoration success has been documented for some restored tidal freshwater wetlands. For example, Simenstad and Thom (1996) found that only a few of 16 ecosystem attributes monitored in a restored tidal freshwater wetland were on a functional trajectory approaching that of reference wetlands. Similarly, ecosystem monitoring at restored tidal freshwater wetlands in the US Pacific Northwest, Fraser River in British Columbia, Louisiana coastal zone, US mid-Atlantic region, and the Yellow River Delta in China indicates that persistent differences exist between restored sites and reference wetlands or design goals (Bartoldus, 1990; Levings and Nishimura, 1997; Quigley, 2001;

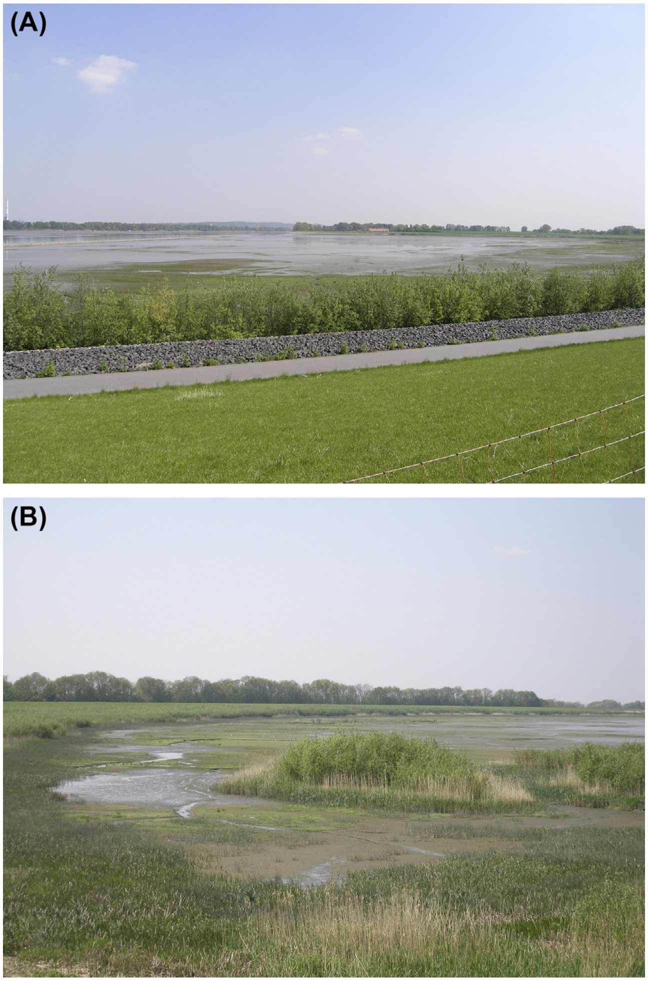

FIGURE 25.1 Hanöfer Sand, a tidal freshwater restoration site on the Elbe River, Germany, constructed in 2004 by excavating and grading soils and de-embanking to reconnect the area to the Elbe (Kai Jensen, pers. comm.). (A) Overview taken from the adjacent sea wall in spring 2008. Large tidal flats dominate the area of the restoration site. Tidal freshwater marshes have been establishing close to the shore. A band-like stand of willows is found directly in front of the dike in the restored area. (B) In accordance with small differences in elevation, a typical zonation of "pioneer," low, and high tidal freshwater marshes has established at the restoration site. At the highest elevation, a small "island" of willows developed, visible near the center. *Photos by Claudia Mählmann.*

Gray et al., 2002; Neff, 2002; Tanner et al., 2002; Adams and Williams, 2004; Wang et al., 2012). Similarly, tidal freshwater wetlands restored for mitigation purposes met some criteria for legal success (vegetation coverage or survival), but not others (hydrology) (Quigley, 2001; Land Management Group, 2004). In areas where natural sites are degraded, restoration may greatly enhance ecosystem structure and function, becoming more similar to natural wetlands (Beauchard et al., 2013a,b). Taken together, however, these findings suggest that

FIGURE 25.2 Two views of tidal freshwater wetlands at Liberty Island in the Sacramento−San Joaquin Bay Delta, California, USA. The site is a historic tidal freshwater wetland that was diked and drained for agriculture, resulting in oxidation of soil organic matter and land subsidence. The dike failed in 1997 during a high-water event and could not be repaired, reconnecting the area to tidal hydrology. This fostered colonization by wetland plants, primarily "tules" (mostly *Schoenoplectus californicus*, with lesser amounts of *Schoenoplectus acutus*). Lateral expansion of plants is mostly vegetative and on the order of 1 m per year. Areas of highly compacted (high bulk density) legacy agricultural soil tend to have lower rates, and high energy (high wind/wave exposure) shorelines have the lowest rates. Percentage of time the substrate is flooded is also an important driver, with deeper marsh edges tending to have lower rates than less flooded areas. Fish species colonizing the site included the endangered species delta smelt (*Hypomesus transpacificus*). Additional details can be found in Lehman et al. (2010), Whitley and Bollens (2014), Sloey et al. (2015), and Hester et al. (2016). *Photos by M.W. Hester.*

there is considerable room for improvement of techniques and approaches for restoration of tidal freshwater wetlands.

Criteria for evaluating restoration or mitigation success have been developed or applied to many types of wetlands, including coastal wetlands (Weinstein et al., 1997; Zhao et al., 2016), nontidal wetlands (Wilson and Mitsch, 1996; Cole and Shafer, 2002), and mitigation banks (Spieles, 2005). Generally, evaluation efforts have focused on soils, hydrology, geomorphology, vegetation development, and wildlife usage. Some studies in salt marshes (Craft et al., 2003) and tidal freshwater wetlands (Simenstad and Thom, 1996; Baldwin and DeRico, 1999) have gone farther, adding quantitative studies of algae, microbial communities, biogeochemical

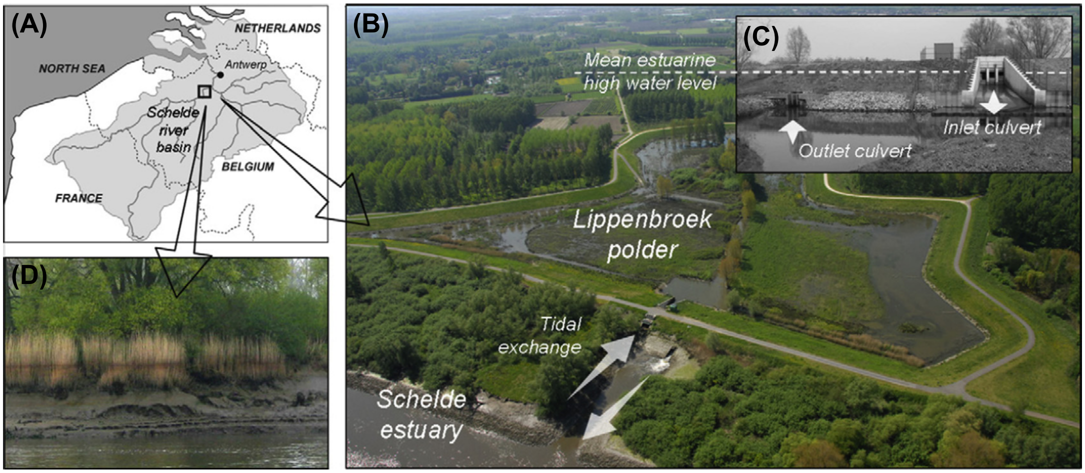

FIGURE 25.3 The controlled reduced tide system on the Scheldt River in Belgium. (A) Location map. (B) The polders, inlet/outlet structures, estuary, and vegetated wetland inside the polders. (C) Close-up of the water exchange system from inside the polder. (D) Typical intertidal gradient in the Scheldt estuary, where erosion prevents vegetation establishment at lower elevations. *Reproduced from Beauchard, O., Jacobs, S., Cox, T.J.S., et al., 2011. A new technique for tidal habitat restoration: evaluation of its hydrological potentials. Ecological Engineering 37, 1849–1858. Used with permission.*

processes, seed banks, invertebrates, fish, or birds as indicators of ecosystem function relative to reference sites. Based on these studies and literature reviewed in Section 2 of this chapter, it is clear that assessments of soil, hydrology, vegetation, and fauna are accepted measures of restoration success used in many types of wetlands, although they are not consistently measured across sites. Here we present success criteria specific to restored tidal freshwater wetlands that address these and related ecosystem attributes (Table 25.2).

As is done for evaluations of other types of restored wetlands, the success criteria we present for restored tidal freshwater wetlands are primarily based on comparisons with reference sites (Craft, 2016). Because success criteria are thus dependent on the condition of the reference site, it is critical to choose reference sites that experience environmental conditions similar to the restored site (Ehrenfeld, 2000a,b). Watershed urbanization or agricultural development may impose landscape constraints on ecosystem components that cannot be overcome through restoration (e.g., Boudell et al., 2015). For this reason, it is unrealistic to expect that restored tidal freshwater wetlands in urbanized landscapes with, for example, high sediment loads, flashy hydrology, fragmented wetlands, and abundant nonnative species will closely resemble those of nonurban landscapes (Baldwin, 2004). The criteria presented in Table 25.2 reflect the need to apply success criteria that can realistically be achieved given environmental constraints imposed by the landscape or watershed surrounding the restored site.

In addition to watershed condition, hydrologic attributes such as tidal range and connectivity to rivers should be similar at the reference and restored sites. If suitable reference sites are not available or evaluated, restored wetlands can be compared with accepted standards

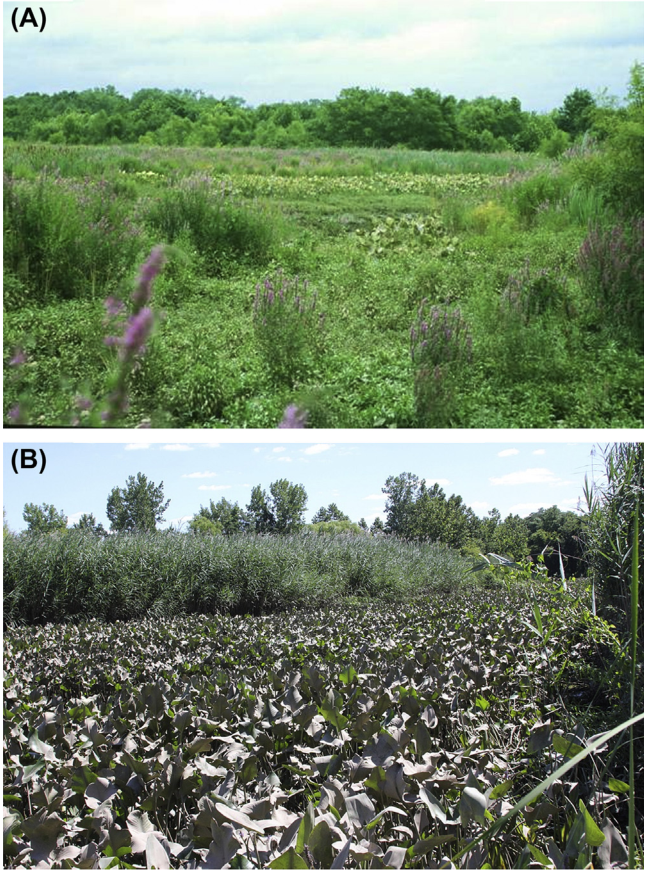

FIGURE 25.4 The Duck Island restored tidal freshwater wetland, Delaware River, Hamilton Township, New Jersey, USA. The 39-ha project site was constructed in 1994 to mitigate highway construction impacts and includes a mix of created tidal and nontidal wetlands and channels and preserved upland areas. (A) Dense and species-rich tidal freshwater herbaceous vegetation in 2001. Purple loosestrife (*Lythrum salicaria*) is visible in clumps in the foreground. (B) Typical view of the wetland in July 2017. Over 2 decades, *Phragmites australis* colonized and formed monocultures across the majority of the site (background), greatly reducing species richness. Tidal channels were planned to be deep enough to be free of emergent vegetation, but sediment eroded from higher elevations increased channel bed elevation and allowed colonization by *Nuphar lutea* (foreground). Detailed descriptions are included in Leck (2003), Leck and Leck (2005), Leck (2012), and Elsey-Quirk and Leck (2015). *(A) Photo by A.H. Baldwin. (B) Photo by M.A. Leck.*

of wetland function (Wilson and Mitsch, 1996) or with literature values for naturally occurring wetlands in similar watersheds.

Some criteria for restoration success may not require comparison with reference sites. Often these are compliance success criteria specified in permit requirements for mitigation projects implemented to replace wetlands lost to development. These may include goals specifying a certain percentage of vegetation cover, a particular hydrologic regime, a preponderance of hydrophytic plant species, use of restored areas by fish and wildlife, or a maximum threshold of nonnative species.

TABLE 25.2 Ecological Criteria for Evaluation of Restored Tidal Freshwater Wetlands

Ecosystem Attribute	Measurements	Evaluation Criteria	Comments
Hydrology	Depth, duration, or percentage of time flooded	Elevation of vegetated high marsh should lie at approximately Mean Sea Level or up to Mean High Water (MHW); vegetated low marsh should lie approximately between Mean Sea Level and Mean Low Water (MLW) (Odum et al., 1984). High marsh should be flooded up to 30 cm depth for 0–4 h per tidal cycle; low marsh should be flooded up to 100 cm depth for 9–12 h per cycle (Simpson et al., 1983; Mitsch and Gosselink, 2000); similar to reference sites.	Differences in elevation of only a few cm (e.g., 3–10) can strongly influence the ability of plants to colonize via seedling recruitment and growth of planted vegetation. Surface elevation relative to Mean Sea Level determines wetland type, for example high marsh vs. low marsh.
Geomorphology	Accretion	Spatially variable; vertical accretion of 5–10 mm year^{-1} (Neubauer et al., 2002), average 6–7 mm year^{-1} (Craft, 2007); similar to reference sites	Restored sites constructed from coarse material (sand and gravel) may not accrete organic matter if elevation is sufficiently high to allow oxidation.
	Elevation change	Little or no net elevation change relative to sea level; similar to reference sites	Naturally occurring tidal freshwater wetlands vary in their ability to accrete vertically at a sufficient elevation to keep pace with rising relative sea level (Craft, 2012; Beckett et al., 2016), and belowground processes of root zone expansion and contraction are particularly important in forested tidal freshwater wetlands, which have hummock-hollow microtopography (Stagg et al., 2016). Excessive erosion, subsidence due to dewatering, or compaction of sediments in restored tidal freshwater wetlands may lead to vegetation species change or dieback; increases in relative sea level may promote vertical increases in elevation by increasing mineral sediment deposition and accumulation of organic matter.
	Channel and pool development	Evidence of small channel formation without excessive erosion or scour of large channels	Large channels cut into restored sites may naturally fill with sediment as small channels form naturally in the wetland (Simenstad and Thom, 1996; Diefenderfer and Montgomery, 2009).
	Topography	Variable within the small range that supports desired vegetation (MLW–MHW)	Naturally occurring tidal freshwater wetlands may exhibit hummocks, particularly in forested systems (15–20 cm height; Baldwin, pers. obs.; Duberstein and Conner, 2009) due to vegetation clumps or fallen trunks, as well as lower areas near channels or in small ponds, but are otherwise very flat.

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TABLE 25.2 Ecological Criteria for Evaluation of Restored Tidal Freshwater Wetlands—cont'd

Ecosystem Attribute	**Measurements**	**Evaluation Criteria**	**Comments**
Soil	Organic matter	Evidence of organic matter accumulation in the surface horizon or streaking into subsurface horizons; average organic carbon concentration for US tidal freshwater marshes is 13%–22% (Craft, 2007)	Sites created by placement of mineral soil or excavation of upland soil to a hydrologically correct elevation may accumulate little organic matter due to oxidation of any material that accumulates vertically; development of organic matter content to the level of nonurban, naturally occurring tidal freshwater wetlands (e.g., 20%–70%, Odum, 1988) may develop extremely slowly (Zedler and Callaway, 1999; Verhoeven et al., 2001; Craft et al., 2003).
		Similar to reference sites	Urban reference sites may have low organic matter content compared with nonurban sites.
	Bulk density	Similar to reference sites	Normally inversely related to organic matter and so tends to be higher in restored than natural tidal freshwater wetlands (e.g., Prasse et al., 2015). Vegetation establishment may reduce bulk density in restored tidal freshwater wetlands (Hester et al., 2016).
	Redox status: redox potential, IRIS tubes, reduced iron test	Similar to reference sites	The degree of soil oxidation and reduction is related to soil hydrology, organic carbon availability, microbial communities, and vegetation, among other variables, and can vary even within a single restored tidal freshwater wetland site (Hester et al., 2016).
	Nutrients, metals, organic contaminants	Similar to reference sites; average nutrient concentrations for US tidal freshwater marshes are 0.9%–1.6% N and 0.9–1.6 mg g −1 P (Craft, 2007)	Concentrations of heavy metals and organic contaminants in dredge material sources should be determined prior to restoration. However, it is unrealistic to try to reduce nutrients or toxins to levels below those of reference sites that experience the same watershed conditions. Metals may accumulate more in woody than in herbaceous vegetation, but overall plants contribute little to phytoremediation (Teuchies et al., 2013).
	Texture	Evidence of surface accumulation of materials of similar texture to reference sites; average bulk density for US tidal freshwater marshes is 0.1–0.3 g cm^{-3} (Craft, 2007)	Sites restored by placing river sediment or excavation of uplands will in general have coarser soil texture (e.g., sand and gravel) than reference sites (silts and clays) (Zedler, 2001).
Salinity	Salinity (parts per 1000, ppt)	Average salinity $\leq$ 0.5 ppt; pulses up to 5 ppt or higher may occur during drought conditions	Saltwater intrusion events that occur only during exceptionally dry years may be important in maintaining plant diversity and may alter fish and invertebrate communities (Odum et al., 1984; Odum, 1988; Baldwin, 2007).

TABLE 25.2 Ecological Criteria for Evaluation of Restored Tidal Freshwater Wetlands—cont'd

Ecosystem Attribute	Measurements	Evaluation Criteria	Comments
Microbial communities and functions	DNA extraction, sequencing	Similar to reference sites	Microbial communities can differ between restored and natural tidal freshwater wetlands, regardless of plant species composition (Prasse et al., 2015). Saltwater intrusion brings in seawater, which contains sulfate. This may shift metabolism toward sulfate reduction and alter decomposition rates (Hopfensperger et al., 2014).
Vegetation	Species composition	The list of perennial species should be similar to those of reference sites, but differences in relative abundance should be accepted	Species such as cattail (*Typha* spp.) are adapted to rapid colonization of exposed, moist substrate such as that created in restored tidal freshwater wetlands; a high abundance of these native highly productive species should be accepted as a natural result of their biology and the environmental conditions created by restoring tidal freshwater wetlands. Species composition of annual species is likely to differ from reference sites because of a lack of seeds of some annual species to colonize; seeding may be required to introduce these species.
		Annual species should comprise 20%–50% of species (Leck et al., 2009), and a peak annual:perennial biomass ratio of 1–5 (Whigham and Simpson, 1992)	Annual species are a key characteristic of many naturally occurring tidal freshwater wetlands (Simpson et al., 1983; Odum et al., 1984). Desired annual species may be slow to colonize restored wetlands sites (Neff and Baldwin, 2005).
	Species richness	Similar to reference sites	Additional plantings or seeding may be necessary if few propagules are present in waterways; nonnative invasive or highly productive native species may contribute substantially to richness in urban areas (Neff, 2002; Rusello, 2006).
	Biomass or total plant cover	Similar to reference sites	Standing biomass and total plant cover are indices of primary production. Belowground biomass may be indicative of adverse physical structure or biochemistry of soils for plant growth. Restoration of submersed aquatic vegetation communities in tidal freshwater areas may require exclosures to prevent transplants from herbivory (Moore et al., 2010). In emergent wetlands, transplanted adults may outperform rhizome plantings and expansion may be altered by hydrology and soil compaction (Sloey et al., 2015).
	Nonnative species abundance	Similar to or less than reference sites	Urban wetlands that might serve as reference sites often contain nonnative plants. Expectations that restored tidal freshwater wetlands in urban areas remain free of nonnative species may be unrealistic (Baldwin, 2004).

Continued

TABLE 25.2 Ecological Criteria for Evaluation of Restored Tidal Freshwater Wetlands—cont'd

Ecosystem Attribute	**Measurements**	**Evaluation Criteria**	**Comments**
Seed banks	Species composition	Dominant species similar to reference sites	Because seed bank composition is related to the composition of vegetation and seeds dispersing to restored sites, watershed characteristics are likely to have a strong influence on seed banks of restored tidal freshwater wetlands and reference sites within the same watershed (Neff et al., 2009).
	Seed density	Similar to reference sites	Higher seed density may occur in restored than in reference tidal freshwater wetland sites (Baldwin and DeRico, 1999; Leck, 2003; Neff et al., 2009).
	Species richness	Similar to reference sites	Richness may be higher in restored than reference sites (Baldwin and DeRico, 1999; Leck, 2003; Neff et al., 2009).
Benthic invertebrates	Density, species composition, species richness	Similar to reference sites	Invertebrate communities, being residential, integrate the water, soil, and vegetation habitat quality functions of the wetland, and are a measure of the capacity of the wetland to support fish, herpetofauna, mammals, and birds. Restoration of tidal freshwater wetlands may improve habitat for macroinvertebrates (Brittingham and Hammerschlag, 2006; Beauchard et al., 2013a).
Fish, birds, mammals, herpetofauna	Density and species composition	Present at restored sites	Restored tidal freshwater wetlands can provide valuable habitat for fish (Whitley and Bollens, 2014), birds (Beauchard et al., 2013b), and other wildlife. It may be useful to document value of wetlands as habitat for particular groups. Comparing restored and reference sites may not be practical because of seasonal and spatial variability in populations. Sampling wetland-dependent guilds may improve resolution.
Ecosystem functions	Nutrient cycling (e.g., mineralization, denitrification)	Similar to reference sites	Removal of invasive plants such as nonnative *Phragmites australis* (in North America) may increase soil ammonium and phosphate concentrations (Meyerson et al., 1999; Findlay et al., 2003).
	Material export and import	Similar to reference sites	Restored tidal freshwater wetlands are net sinks for nitrate and ammonium and net exporters of silica, but different sites vary in import or export of organic N and C, phosphorus, and particulates (Van Damme et al., 2009; Lehman et al., 2010). Restored tidal freshwater wetlands may be important in buffering dissolved silicon loading to estuaries, increasing resilience of diatom communities (Jacobs et al., 2013).

If the restored site is in an urbanized (or agricultural) landscape, reference sites should also be located in an urban (or agricultural) landscape with similar watershed characteristics. If reference sites are not available, restored sites can be compared to accepted standards of wetland function (Wilson and Mitsch, 1996) or literature values for naturally occurring wetlands in similar watersheds or landscapes.

4. RESTORED TIDAL FRESHWATER WETLANDS OF THE ANACOSTIA RIVER, WASHINGTON, DC

4.1 Characteristics of Restored and Reference Tidal Freshwater Wetland Sites

As is the case for many urban rivers, the ecosystems of the Anacostia River in Washington, DC, have been substantially altered by human activities. Development and related projects such as flood control, mandated dredging, sea wall construction, and landfills destroyed more than 3900 ha of forested and herb-dominated wetlands, including about 1000 ha of tidal freshwater wetlands along the Anacostia River (Schmid, 1994; U.S. EPA, 1997), leaving only a few hectares of fragmented tidal freshwater wetlands. Several tidal freshwater wetland restoration projects have been implemented, including Kenilworth Marsh, Kingman Marsh, and Anacostia River "fringe" wetlands (Fig. 25.5). Historically a tidal freshwater wetland existed at the location of Kenilworth Marsh, but the site was dredged to create a recreational lake in the 1940s (Syphax and Hammerschlag, 1995). The US Army Corps of Engineers (USACE) restored wetlands at the site in 1992–93 by pumping about 115,000 m^3 of sediment dredged from the adjacent Anacostia River into containment cells and planting more than 340,000 plants of 16 species (Bowers, 1995; Syphax and Hammerschlag, 1995). At Kingman Marsh, the USACE restored tidal freshwater wetlands in early 2000 in a similar fashion by placing Anacostia River sediment and planting 750,000 plants of seven species. This work created about 13 ha of vegetated wetland (AWRC, 2002). Sediment elevations were designed to be lower than those at Kenilworth Marsh to reduce colonization by nonnative invasive or highly productive native species that form large monoclonal patches (including *Lythrum salicaria*, *Phragmites australis*, and *Typha* spp.).

As part of postconstruction monitoring for the Kingman Marsh project, two natural tidal freshwater wetlands with similar tidal ranges were selected as reference sites to provide a basis for evaluating ecosystem development in the restored wetlands. One of these sites, Dueling Creek Marsh, is a remnant 0.41 ha urban wetland located on a small tributary to the Anacostia River just 0.8 km upstream of Kenilworth Marsh. The other site, Patuxent Wetland Park, is a nonurban tidal freshwater wetland located along the Patuxent River in an adjacent watershed. Furthermore, a multiyear exclosure experiment has been conducted at Kingman Marsh to study the effects of resident Canada geese on marsh vegetation (Krafft et al., 2013). Surface elevation table–marker horizon sampling stations (Boumans and Day, 1993; Cahoon et al., 1995, 1996; 2002a,b) were also installed as a means of tracking sedimentation, elevation change, and geomorphic processes at all of the study locations.

4.2 Evaluation of Success of Restored Tidal Freshwater Wetlands

The goal of ecosystem monitoring at Kingman was to "document both the status and the degree to which the reconstructed marsh achieved a wetland condition similar to reference emergent freshwater tidal wetland habitat" (Hammerschlag et al., 2006). Information from monitoring studies is used here to evaluate the success of restored Anacostia wetlands (see Table 25.3 for details and additional literature references).

Restoration of tidal freshwater wetlands in the Anacostia watershed was successful in creating hydrology similar to that of rural or urban reference sites (Baldwin et al., 2009).

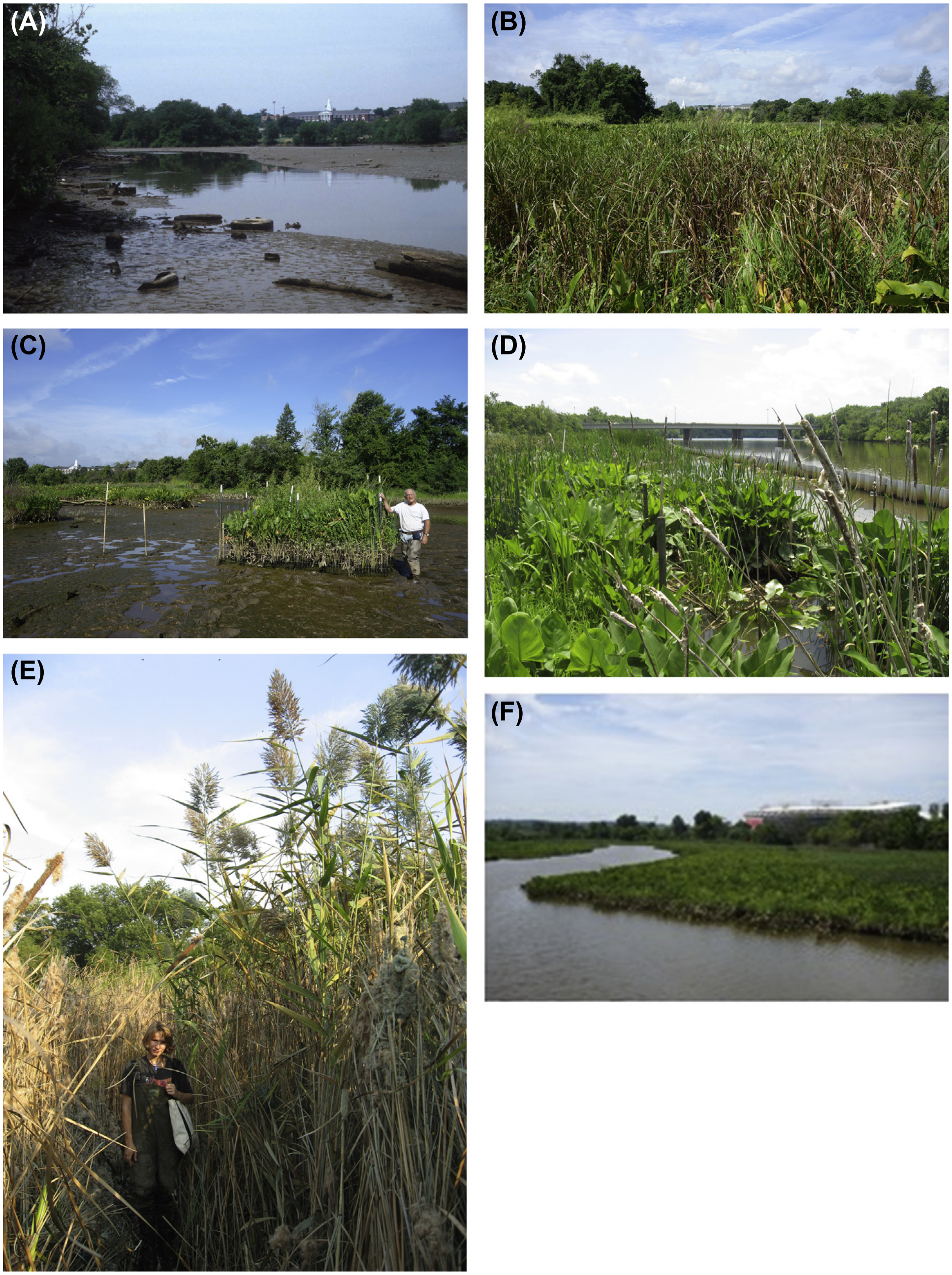

FIGURE 25.5 Views of Anacostia River restored tidal freshwater wetlands. (A) Kingman Marsh prerestoration in 1999; the site was mostly mudflat at low tide and open water at high tide. Restoration was implemented by pumping in river sediment to raise elevation and planting with native species. (B) In 2016, many parts of Kingman remain vegetated; see white building dome landmark also in panels C and A. (C) Exclosure fences demonstrate the complete loss of emergent vegetation in other parts of Kingman due to herbivory by Canada geese (photo: 2016). (D) Anacostia Fringe wetlands relied on sheet piling (visible at right) to prevent erosion and goose fencing (including overhead strings to deter geese) to create desired vegetation (photo: 2008). (E) Kenilworth Marsh achieved dense vegetation but there are large monoculture stands of *Typha* spp. and nonnative *Phragmites australis* (photo: 2007). (F) Some of the restored Heritage Island marshes have been persistently vegetated (2016). Additional details are in Baldwin and DeRico (1999), Neff et al. (2009), and Prasse et al. (2015). *Photos by A.H. Baldwin.*

TABLE 25.3 Evaluation of Restored Tidal Freshwater Wetlands on the Anacostia River, Washington, DC

Parameter	Summary of Monitoring Results	Evaluation
Hydrology	Flooding duration at one of the restored sites (Kingman) was similar to that at a rural reference site (Patuxent), but more prolonged than at an urban reference site (Dueling Creek), which was similar to the older restored site (Kenilworth) (Baldwin et al., 2009).	Because Dueling Creek is in the same watershed as the restored sites, it is probably a more appropriate reference site than the rural reference sites. However, the Kingman restoration was successful in restoring hydrology similar to that in a nonurbanized watershed.
Geomorphology	Surface elevation table and marker horizon measurements were made at five locations at two restored wetlands (Kingman and Kenilworth) over a 3-year period beginning in October 2002, about $2^1/_2$ years after sediment placement. At both wetlands, accretion rates were >20 mm year^{-1} and were at least double the rate of elevation gain, indicating subsurface subsidence but still net elevation gain (Baldwin et al., 2009).	The two restored tidal freshwater wetlands accumulated sediments and grew vertically at rates greater than relative sea level rise (3.22 mm year^{-1}; Washington, DC, tide gage 8594900, 1924–2015; tidesandcurrents.gov, accessed 13 January 2017), despite ongoing consolidation of the dredged material substrate (Baldwin et al., 2009). The slower rates of accretion and elevation gain at Kenilworth are consistent with its higher position within the tidal range (less mineral sedimentation and more organic matter decomposition). Rates of elevation increase were 7–8 mm year^{-1} at a natural tidal freshwater wetland on the Patuxent River (Beckett, 2012), but natural tidal freshwater wetlands in other areas are not keeping pace with sea level rise (Craft, 2012; Beckett et al., 2016). Salinity intrusion is likely to have the largest long-lasting impact and may interact with other variables such as atmospheric warming, elevated CO_2, and eutrophication to change the distribution and ecosystem structure and function of tidal freshwater wetlands (Neubauer and Craft, 2009).
Soil	Soil organic matter (SOM) content was only 2.5% at an urban restored tidal freshwater wetland (Kingman), about 12 years following restoration, and 5% at a nearby restored tidal freshwater wetland (Kenilworth), about 20 years after restoration (Prasse et al., 2015).	Although SOM at a rural reference site (Patuxent) was >15%, an urban reference site (Dueling) near the restored sites had only 6% (Prasse et al., 2015), suggesting that accumulation of SOM to higher levels may not be possible in highly urbanized watersheds.
Microbial communities	The two restored sites, Kingman and Kenilworth, had similar community composition and functional gene abundance even though they differed in age (Prasse et al., 2015).	The urban reference site (Dueling) was more similar in composition to the natural reference site (Patuxent) than to the two urban restored sites (Prasse et al., 2015). Thus, microbial communities may require many years to develop.

Continued

TABLE 25.3 Evaluation of Restored Tidal Freshwater Wetlands on the Anacostia River, Washington, DC—cont'd

Parameter	Summary of Monitoring Results	Evaluation
Vegetation	Plant community monitoring revealed significant loss of vegetation cover, species richness, and diversity at a restored site that experienced substantial herbivory from Canada geese (Kingman; Baldwin et al., 2009) but not at any of the other restored or natural wetlands studied (Rusello, 2006; Paul et al., 2006). Most of the dominant species at the urban restored sites (Kingman and Kenilworth) were also dominant at the urban reference site (Dueling; Baldwin et al., 2009). These include the nonnative purple loosestrife *Lythrum salicaria* and the highly productive *Phalaris arundinacea*, neither of which occurred at the rural reference site (Patuxent). *Phragmites australis* and *Typha* spp. were both dominant features of the vegetation community at Kenilworth and have expanded at Kingman.	Populations of resident Canada geese were 3–5 times larger in the area of Kingman than Kenilworth (Paul et al., 2006). The annual species *Impatiens capensis* occurred at both restored and reference sites. However, *Polygonum arifolium* and *Polygonum sagittatum*, which were dominant at one or both reference sites, were rare at the restored sites. The urban reference site also contained nonnative invasive and highly productive native plants occurring at the restored sites, indicating that these are an expected persistent feature of any restored tidal freshwater wetlands in highly urbanized watersheds.
Seed bank	Surface soil samples were collected from restored and reference sites in 2000, 2001, and 2003 for seed bank analysis using the emergence method (Baldwin et al., 1996, 2001; Baldwin and DeRico, 1999; Leck, 2003). The seed bank at one restored site (Kingman) developed rapidly during the first growing season, showing large increases in emerging seedling density and taxa richness between 2000 and 2001 (Neff et al., 2009).	In 2003, all restored and reference sites were found to be similar in density and taxa richness. Significantly higher seedling density and species density were also found at a created tidal wetland in Delaware after 1 year of development (Leck, 2003). Seeds of the nonnative plant *Lythrum salicaria* were important at all urban sites in 2003.
Benthic invertebrates	Benthic macroinvertebrate organisms were collected over a 3-year period (2001–04) using an Ekman bottom grab sampler, sediment corer, dip-net, and Hester-Dendy sampler (Brittingham and Hammerschlag, 2006). Macroinvertebrate density was significantly greater at the newer restored site (Kingman) than at the older restored sited (Kenilworth) due to more numerous chironomids and oligochaetes (Brittingham and Hammerschlag, 2006).	Macroinvertebrate taxa composition at the older restored site (Kenilworth) was similar to that of the urban reference site, although richness was higher. The rural reference site (Patuxent) had more diversity, containing representatives from 30 families, whereas all of the urban restored and reference sites combined had only 23 families.
Birds	A total of 137 bird species were observed at Kingman and 164 at Kenilworth (177 species total); 124 of the species occurred at both wetlands (Paul et al., 2006).	Although birds were not studied at reference sites, results indicate that both restored wetlands provide habitat for numerous species.

The Kingman restored tidal freshwater wetland gained in elevation at rates greater than relative sea level rise (likely due to high sediment levels in the tidal Anacostia), indicating the wetlands are likely to persist as long as the rate of sea level rise does not increase (Baldwin et al., 2009). This outcome is in contrast to natural tidal freshwater wetlands on the US Atlantic Coast, which may not be keeping pace with rising seas. Accumulation of soil organic matter at the restored tidal freshwater wetlands has been slow, as is widely found in wetland restoration projects, but approaching levels at the urban reference site (Prasse et al., 2015). It is unlikely that the restored sites will ever attain soil organic matter similar to tidal freshwater wetlands in rural settings because of constraints imposed by the urban environment (Baldwin et al., 2009). Microbial communities developed slowly in restored sites and remained different from urban and rural reference sites even after 20 years (Prasse et al., 2015). Vegetation has also been constrained by the urban environment, as indicated by heavy grazing pressure from nonmigratory ("resident") geese at one site and by the establishment and expansion of nonnative plant species at all urban restored and reference sites (Rusello, 2006; Paul et al., 2006). The seed bank of restored tidal freshwater wetlands developed rapidly and converged with that of the urban reference site within a few years (Neff et al., 2009). Macroinvertebrate composition was dominated by chironomids and oligochaetes and appeared to be converging with that of the urban reference site but remained at lower taxa richness and had different distribution of dominant species than the rural natural site (Brittingham and Hammerschlag, 2006). Both restored wetlands provided habitat for a variety of bird species, including Canada goose, great blue heron, great egret, American green-winged teal, mallard, greater yellowlegs, song sparrow, killdeer, ring-billed herring, and laughing gulls (Paul et al., 2006).

5. CONCLUSIONS AND IMPLICATIONS

5.1 Restoration of Tidal Freshwater Wetlands in Urban Landscapes and Selection of Urban Reference Sites

Tidal freshwater wetlands typically have higher plant diversity than brackish or saline wetlands (Chapter 18 by Whigham et al.), creating unique challenges for restoration efforts. Monitoring at restored tidal freshwater wetland sites has demonstrated that restoration of elevation, hydrology, vegetation, geomorphological characteristics and processes, and faunal communities is possible and can be considered successful to varying degrees (e.g., Simenstad and Thom, 1996; Beauchard et al., 2013a,b). The case study of the Anacostia River tidal freshwater wetlands in Washington, DC highlights the difficulties of reestablishing wetland structure and function in an urbanized landscape (particularly as overshadowed by the large resident Canada goose population) (Baldwin, 2004). Thus, altered hydrology, environmental pollutants, fragmented landscapes, and nonnative species can override efforts to restore tidal freshwater wetlands to a structure similar to naturally occurring tidal freshwater wetlands in nonurban areas. For urban restoration projects, therefore, it makes sense to be realistic in setting goals and to consider urban reference sites (Ehrenfeld, 2000a,b).

5.2 Establishment of Vegetation

Because restoration efforts typically involve extensive earthmoving (e.g., excavation, dredged material placement, grading) and subsequent rapid changes in geomorphology related to tidal scouring, sedimentation, or compaction, a phased approach to wetland restoration is likely to improve success. Increases in inundation due to erosion or subsidence may reduce survival of plantings over time, but plantings may also help to reduce erosion. By completing sediment placement, excavation, and grading before or during the dormant season, sediment compaction and dewatering can occur for several months prior to the growing season. A topographic survey completed at this time will allow determination of suitability of elevation for plant growth, and additional grading can be performed or sediment placed before or during the early spring. While many species are likely to disperse to restored tidal freshwater wetlands (Neff and Baldwin, 2005), planting or seeding of native species not expected in dispersal pathways may be necessary during the spring to rapidly establish desired species, stabilize sediments against erosion, and possibly reduce establishment of nonnative species.

If herbivores such as resident Canada geese are present at or nearby restoration sites, it may be necessary to reduce those populations through management or protect sites with fencing for several years until vegetation has established. Dense vegetation dominated by native species has established at two other restored tidal freshwater wetland projects in the Anacostia (Heritage Island and River Fringe, Fig. 25.5), where geese have been excluded (Hammerschlag, pers. obs.). A multiyear study at Kingman Marsh has conclusively and strongly demonstrated the strong effect of grazing by geese on marsh vegetation (Fig. 25.5, Krafft et al., 2013). When geese were excluded, sites with planted vegetation persisted and unplanted areas were rapidly colonized and reached about 60% cover in 2 years (Krafft et al., 2013). In unfenced areas, cover of planted vegetation was reduced from about 100% to about 20% in a single year (Krafft et al., 2013). The strong impact of Canada geese on plant communities, particularly annual species, has also been documented in natural tidal freshwater wetlands (Baldwin and Pendleton, 2003; Haramis and Kearns, 2007).

5.3 Control of Nonnative Species

The benefits of controlling nonnative species in restored wetlands should be weighed against the negative environmental impacts of chemical use, as well as labor and materials costs, particularly if the nonnative species also occur in reference wetlands. Furthermore, the beneficial ecological functions of nonnative species should be considered in decisions regarding their control. However, governmental agencies and conservation groups may emphasize establishment of a diversity of local native plants, so it may be necessary to support efforts to suppress nonnative invasive or highly productive native species to promote a habitat that reflects these project goals.

The Anacostia experience suggests that elevations at or just below mean high tide will support a number of native high marsh species but will reduce the vigor of aggressive high marsh species. In contrast, at a restored tidal freshwater wetland in New Jersey, USA, the nonnative lineage of *Phragmites australis* gradually colonized 85%–95% of the wetland over an approximately 20-year period, replacing two earlier invasive colonizers, *Lythrum salicaria* and *Phalaris arundinacea*, and was associated with decreasing species richness (Mary Leck, pers. comm.; Leck, 2012; Elsey-Quirk and Leck, 2015). An exception was low-elevation areas colonized by the flood-tolerant native plant *Nuphar lutea* (Fig. 25.3B; Mary Leck, pers. comm.). *Phragmites*-free patches within the site contained diverse plant communities (Leck, 2012), suggesting that *Phragmites* control would increase diversity in some restored sites.

5.4 Implications for Restoration of Tidal Freshwater Wetlands

In a larger context, this review brings to light a number of considerations that are likely to improve the success of tidal freshwater wetlands restoration:

- *Clear objectives or goals for restoration during the early planning stages*. This need has been stated repeatedly for wetland restoration in general (e.g., Mitsch and Gosselink, 2000; Zedler, 2001), and it applies equally to tidal freshwater wetland restoration.
- *Realistic criteria for success in meeting goals or objectives*, preferably with regard to appropriately chosen reference sites. Planners may envision a pristine, diverse, exotic species-free wetland as the goal, but this may not be possible in a highly urbanized or agricultural landscape (Ehrenfeld, 2000b; Baldwin, 2004).
- *Increased use of adaptive management* for several years following restoration, for example, to fine-tune elevations, introduce additional plantings or seeds, or spot-control nonnative plants.
- *Restoration of tidal freshwater wetlands viewed ecologically as catastrophic landscape disturbances* that create high-light, high-nutrient, moist soil conditions optimal for rapid colonization by native and nonnative wetland species adapted to colonizing disturbed substrates. These species can be viewed as a natural initial phase of vegetation and community development, with the expectation that vegetation development will continue for many years, as influenced by hydrology, geomorphology, seed and propagule supply, and watershed condition.
- *Postconstruction monitoring* not only to document level of success but also to highlight situations that may require adjustment for better outcomes.

Restoration of tidal freshwater wetlands is increasingly practiced in North America and Eurasia. Because of the biological and hydrogeological complexity of tidal freshwater wetlands, outcomes of restoration are often uncertain, although the studies reviewed here demonstrate success in restoring structure and function at many tidal freshwater wetland sites. We hope that the success criteria proposed here stimulate discussion and promote dissemination of information improving the restoration potential of these wetlands.

References

Adams, M.A., Williams, G.L., 2004. Tidal marshes of the Fraser River estuary: composition, structure, and history of marsh creation efforts to 1997. In: Groulx, B.J., Mosher, D.C., Luternauer, J.L., Bilderback, D.E. (Eds.), Fraser River Delta, British Columbia: Issues of an Urban Estuary, Geological Survey of Canada Bulletin 567 Geological Survey of Canada, Vancouver, British Columbia, pp. 147–172.

AWRC (Anacostia Watershed Restoration Committee), 2002. Working Together to Restore the Anacostia Watershed, 2001 Annual Report. Washington, DC.

Baldwin, A.H., 2004. Restoring complex vegetation in urban settings: the case of tidal freshwater marshes. Urban Ecosystems 7, 125−137.

Baldwin, A.H., 2007. In: Conner, W., Doyle, T., Krauss, K. (Eds.), Vegetation and Seed Bank Studies of Salt-pulsed Swamps of the Nanticoke River, Chesapeake Bay. Springer-Verlag, Berlin, Germany, pp. 139−160.

Baldwin, A.H., 2009. Restoration of tidal freshwater wetlands in North America. In: Barendregt, A., Whigham, D.F., Baldwin, A.H. (Eds.), Tidal Freshwater Wetlands. Backhuys Publishers, Leiden, The Netherlands, pp. 207−222.

Baldwin, A.H., DeRico, E.F., 1999. The seed bank of a restored tidal freshwater marsh in Washington, DC. Urban Ecosystems 3, 5−20.

Baldwin, A.H., Pendleton, F.N., 2003. Interactive effects of animal disturbance and elevation on vegetation of a tidal freshwater marsh. Estuaries 26, 905−915.

Baldwin, A.H., McKee, K.L., Mendelssohn, I.A., 1996. The influence of vegetation, salinity, and inundation on seed banks of oligohaline coastal marshes. American Journal of Botany 83, 470−479.

Baldwin, A.H., Egnotovich, M.S., Clarke, E., 2001. Hydrologic change and vegetation of tidal freshwater marshes: field, greenhouse, and seed-bank experiments. Wetlands 21, 519−531.

Baldwin, A.H., Hammerschlag, R.S., Cahoon, D.R., 2009. Evaluation of restored tidal freshwater wetlands. In: Perillo, G.M.E., Wolanski, E., Cahoon, D.R., Brinson, M.M. (Eds.), Coastal Wetlands: An Integrated Ecosystem Approach, first ed. Elsevier, Oxford, UK, pp. 801−832.

Barendregt, A., Whigham, D.F., Baldwin, A.H., et al., 2006. Wetlands in the tidal freshwater zone. In: Bobbink, R., Beltman, B., Verhoeven, J.T.A., Whigham, D.F. (Eds.), Wetlands: Functioning, Biodiversity Conservation, and Restoration. Springer-Verlag, Berlin, pp. 117−148.

Bartoldus, C.C., 1990. Revegetation and Production in a Constructed Freshwater Tidal Marsh (PhD dissertation). George Mason University, Fairfax, VA.

Bartoldus, C.C., Heliotis, F.D., 1989. Factors affecting survival of planted materials in Marley Creek constructed freshwater tidal marsh, Maryland. Transportation Research Record 1224, 1−5.

Beauchard, O., Jacobs, S., Cox, T.J.S., et al., 2011. A new technique for tidal habitat restoration: evaluation of its hydrological potentials. Ecological Engineering 37, 1849−1858.

Beauchard, O., Jacobs, S., Ysebaert, T., et al., 2013a. Sediment macroinvertebrate community functioning in impacted and newly-created tidal freshwater habitats. Estuarine, Coastal and Shelf Science 120, 21−32.

Beauchard, O., Jacobs, S., Ysebaert, T., et al., 2013b. Avian response to tidal freshwater habitat creation by controlled reduced tide system. Estuarine, Coastal and Shelf Science 131, 12−23.

Beckett, L.H., 2012. Subsidence, Accretion, and Elevation Trends in Estuarine Wetlands and Relationships to Salinity and Sediment Stratigraphy (PhD dissertation). University of Maryland, College Park.

Beckett, L.H., Baldwin, A.H., Kearney, M.S., 2016. Tidal marshes across a Chesapeake Bay subestuary are not keeping up with sea-level rise. PLoS One 11, e0159753 doi:10.1371.journal.pone.0159753.

Boudell, J.A., Dixon, M.D., Rood, S.B., Stromberg, J.C., 2015. Restoring functional riparian ecosystems: concepts and applications. Ecohydrology 8, 747−752.

Boumans, R., Day Jr., J.W., 1993. High precision measurements of sediment elevation in shallow coastal areas using a sedimentation-erosion table. Estuaries 16, 375−380.

Bowers, J.K., 1995. Innovations in tidal marsh restoration: the Kenilworth Marsh account. Restoration and Management Notes 13, 155−161.

Brittingham, K.D., Hammerschlag, R.S., 2006. Benthic Macroinvertebrate Communities of Reconstructed Freshwater Tidal Wetlands in the Anacostia River, Washington, D.C. Final Report (2002-2004). U.S. Geological Survey Patuxent Wildlife Research Center, Beltsville, Maryland.

Cahoon, D.R., Reed, D.J., Day Jr., J.W., 1995. Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and Barghoorn revisited. Marine Geology 128, 1−9.

Cahoon, D.R., Lynch, J.C., Knaus, R.M., 1996. Improved cryogenic coring device for sampling wetland soils. Journal of Sedimentary Research 66, 1025−1027.

Cahoon, D.R., Lynch, J.C., Hensel, P., et al., 2002a. High-precision measurements of wetland sediment elevation: I. Recent improvements to the Sedimentation-Erosion Table. Journal of Sedimentary Research 72, 730−733.

Cahoon, D.R., Lynch, J.C., Perez, B.C., et al., 2002b. High-precision measurements of wetland sediment elevation: II. The rod surface elevation table. Journal of Sedimentary Research 72, 734−739.

Cole, C.A., Shafer, D., 2002. Section 404 wetland mitigation and permit success criteria in Pennsylvania, USA, 1986-1999. Environmental Management 30, 508−515.

Cox, T., Maris, T., De Vleeschauwer, P., et al., 2006. Flood control areas as an opportunity to restore estuarine habitat. Ecological Engineering 28, 55–63.

Craft, C., 2007. Freshwater input structures soil properties, vertical accretion, and nutrient accumulation of Georgia and U.S. tidal marshes. Limnology and Oceanography 52, 1220–1230.

Craft, C.B., 2012. Tidal freshwater forest accretion does not keep pace with sea level rise. Global Change Biology 18, 3615–3623.

Craft, C., 2016. Creating and Restoring Wetlands: From Theory to Practice. Elsevier, Amsterdam.

Craft, C., Megonigal, P., Broome, S., et al., 2003. The pace of ecosystem development of constructed *Spartina alterniflora* marshes. Ecological Applications 13, 1417–1432.

David, A.T., Ellings, C.S., Woo, I., et al., 2014. Foraging and growth potential of juvenile Chinook Salmon after tidal restoration of a large River delta. Transactions of the American Fisheries Society 143, 1515–1529.

Diefenderfer, H.L., Montgomery, D.R., 2009. Pool spacing, channel morphology, and the restoration of tidal forested wetlands of the Columbia River, U.S.A. Restoration Ecology 17, 158–168.

DNREC (Delaware Department of Natural Resources and Environmental Control), 2016. Northern Delaware Wetland Rehabilitation Program. New Castle, DE.

Duberstein, J.A., Conner, W.H., 2009. Use of hummocks and hollows by trees in tidal freshwater forested wetlands along the Savannah River. Forest Ecology Management 258, 1613–1618.

Ehrenfeld, J.G., 2000a. Evaluating wetlands within an urban context. Urban Ecosystems 4, 69–85.

Ehrenfeld, J.G., 2000b. Defining the limits of restoration: the need for realistic goals. Restoration Ecology 8, 2–9.

Elsey-Quirk, T., Leck, M.A., 2015. Patterns of seed bank and vegetation diversity along a tidal freshwater river. American Journal of Botany 102, 1996–2012.

Findlay, S., Groffman, P., Dye, S., 2003. Effects of *Phragmites australis* removal on marsh nutrient cycling. Wetlands Ecology and Management 11, 157–165.

French, P.W., 2006. Managed realignment – the developing story of a comparatively new approach to soft engineering. Estuarine, Coastal and Shelf Science 67, 409–423.

Gannett Fleming, 2001. Plans of Route 29-Open Water Mitigation, Township of Hamilton, County of Mercer. Gannett Fleming, Inc., Hammonton, NJ.

Gray, A., Simenstad, C.A., Bottom, D.L., et al., 2002. Contrasting functional performance of juvenile salmon habitat in recovering wetlands of the Salmon River estuary, Oregon, U.S.A. Restoration Ecology 10, 514–526.

Grout, J.A., Levings, C.D., Richardson, J.S., 1997. Decomposition rates of purple loosestrife (*Lythrum salicaria*) and Lyngbyei's sedge (*Carex lyngbyei*) in the Fraser River estuary. Estuaries 20, 96–102.

Hammerschlag, R.S., Baldwin, A.H., Krafft, C.C., et al., 2006. Five Years of Monitoring Reconstructed Freshwater Tidal Wetlands in the Urban Anacostia River (2000–2004). U.S. Geological Survey Patuxent Wildlife Research Center, Beltsville, MD.

Haramis, G.M., Kearns, G.D., 2007. Herbivory by resident geese: the loss and recovery of wild rice along the tidal Patuxent river. The Journal of Wildlife Management 71, 788–794.

Hester, M.W., Willis, J.M., Sloey, T.M., 2016. Field assessment of environmental factors constraining the development and expansion of *Schoenoplectus californicus* marsh at a California tidal freshwater restoration site. Wetlands Ecology and Management 24, 33–44.

Hopfensperger, K.N., Burgin, A.J., Schoepfer, V.A., et al., 2014. Impacts of saltwater incursion on plant communities, anaerobic microbial metabolism, and resulting relationships in a restored freshwater wetland. Ecosystems 17, 792–807.

Jacobs, S., Beauchard, O., Struyf, E., et al., 2009. Restoration of tidal freshwater vegetation using controlled reduced tide (CRT) along the Schelde Estuary (Belgium). Estuarine, Coastal and Shelf Science 85, 368–376.

Jacobs, S., Müller, F., Teuchies, J., et al., 2013. The vegetation silica pool in a developing tidal freshwater marsh. Silicon 5, 91–100.

Kaminsky, M., Scelsi, P., 1986. Route 130, Section 9F Rancocas Creek Bridge, Site III Wetland Replacement. Bureau of Environmental Analysis. New Jersey Department of Transportation, Trenton, NJ.

Kentula, M.E., 2000. Perspectives on setting success criteria for wetland restoration. Ecological Engineering 15, 199–209.

Kistritz, R., 1996. Habitat Compensation, Restoration and Creation in the Fraser River Estuary: Are We Achieving a No-Net-Loss of Fish Habitat? R.U. Kistritz Consultants Ltd., Richmond, British Columbia.

Krafft, C.C., Hatfield, J.C., Hammerschlag, R.S., 2013. Effects of Canada Goose Herbivory on the Tidal Freshwater Wetlands in Anacostia Park, 2009−2011. Natural Resource Technical Report, NPS/NCR/NCRO/NRTR—2013/001). United States Department of the Interior, National Park Service, Washington, DC.

Land Management Group, 2004. McIntyre Tract: Year Four Monitoring Report, Brunswick County, North Carolina. Land Management Group, Inc., Wilmington, NC.

Lane, R.R., Day Jr., J.W., Thibodeaux, B., 1999. Water quality analysis of a freshwater diversion at Caernarvon, Louisiana. Estuaries 22, 327−336.

Leck, M.A., 2003. Seed-bank and vegetation development in a created tidal freshwater wetland on the Delaware River, Trenton, New Jersey, USA. Wetlands 23, 310−343.

Leck, M.A., 2012. Dispersal potential of a tidal river and colonization of a created tidal freshwater marsh. AoB Plants 5, pls050. https://doi.org/10.1093/aobpla/pls050.

Leck, M.A., Leck, C.F., 2005. Vascular plants of a Delaware River tidal freshwater wetland and adjacent terrestrial areas: seed bank and vegetation comparisons of reference and constructed marshes and annotated species list. Journal of the Torrey Botanical Society 132, 323−354.

Leck, M.A., Baldwin, A.H., Parker, V.T., et al., 2009. Plant communities of North American tidal freshwater wetlands. In: Barendregt, A., Whigham, D.F., Baldwin, A.H. (Eds.), Tidal Freshwater Wetlands. Backhuys, Leiden, The Netherlands.

Lehman, P.W., Mayr, S., Mecum, L., et al., 2010. The freshwater tidal wetland Liberty Island, CA was both a source and sink of inorganic and organic material to the San Francisco Estuary. Aquatic Ecology 44, 359−372.

Levings, C.D., Nishimura, D.J.H., 1996. Created and Restored Sedge Marshes in the Lower Fraser River and Estuary: An Evaluation of Their Functioning as Fish Habitat. Department of Fisheries and Oceans, West Vancouver, British Columbia.

Levings, C.D., Nishimura, D.J.H., 1997. Created and restored marshes in the lower Fraser River, British Columbia: summary of their functioning as fish habitat. Water Quality Research Journal Canada 32, 599−618.

Marble and Company, 1998. Post-Construction Wetland Monitoring Report, Trenton Complex Mitigation Site, Mercer County, New Jersey. A.D. Marble and Company, Inc., Rosemont, PA.

Meyerson, L.A., Chambers, R.M., Vogt, K.A., 1999. The effects of *Phragmites* removal on nutrient pools in a freshwater tidal marsh ecosystem. Biological Invasions 1, 129−136.

Mitsch, W.J., Gosselink, J.G., 2000. Wetlands, third ed. John Wiley and Sons, NY.

Mitsch, W.J., Wilson, R.F., 1996. Improving the success of wetland creation and restoration with know-how, time, and self-design. Ecological Applications 6, 77−83.

Moore, K.A., Shields, E.C., Jarvis, J.C., 2010. The role of habitat and herbivory on the restoration of tidal freshwater submerged aquatic vegetation populations. Restoration Ecology 18, 596−604.

Neff, K.P., 2002. Plant Colonization and Vegetation Change in a Restored Tidal Freshwater Wetland in Washington, DC (M.S. thesis). University of Maryland, College Park, Maryland.

Neff, K.P., Baldwin, A.H., 2005. Seed dispersal into wetlands: techniques and results for a restored tidal freshwater marsh. Wetlands 25, 392−404.

Neff, K.P., Rusello, K., Baldwin, A.H., 2009. Rapid seed bank development in restored tidal freshwater wetlands. Restoration Ecology 17, 539−548.

Neubauer, S.C., Craft, C.B., 2009. Global change and tidal freshwater wetlands: scenarios and impacts. In: Barendregt, A., Whigham, D.F., Baldwin, A.H. (Eds.), Tidal Freshwater Wetlands. Backhuys, Leiden, The Netherlands.

Neubauer, S.C., Anderson, I.C., Constantine, J.A., et al., 2002. Sediment deposition and accretion in a mid-Atlantic (USA) tideal freshwater marsh. Estuarine, Coastal and Shelf Science 54, 713−727.

Odum, W.E., 1988. Comparative ecology of tidal freshwater and salt marshes. Annual Review of Ecology and Systematics 19, 147−176.

Odum, W.E., Smith III, T.J., Hoover, J.K., et al., 1984. The Ecology of Tidal Freshwater Marshes of the United States East Coast: A Community Profile. FWS/OBS-83/17. U.S. Fish and Wildlife Service, Washington, DC.

Orr, M., Crooks, S., Williams, P.B., 2003. Will restored tidal marshes be sustainable? San Franciso Estuary and Watershed Science 1, 1−33.

Paul, M.M., Krafft, C.C., Hammerschlag, R.S., 2006. Avian Comparisons Between Kingman and Kenilworth Marshes, Final Report 2001−2004. U.S. Geological Survey Patuxent Wildlife Research Center, Beltsville, MD.

Phillip, M., 2005. Decker Island Wildlife Area: Enhancing Delta Wetlands One Phase at a Time. Outdoor California March − April, pp. 4−8.

Prasse, C.E., Baldwin, A.H., Yarwood, S.A., 2015. Site history and edaphic features override the influence of plant species on microbial communities in restored tidal freshwater wetlands. Applied and Environmental Microbiology 81, 3482–3491.

Quigley, P.A., 2001. Wetlands Monitoring Report, Henderson Freshwater Tidal Wetland Restoration, John Heinz National Wildlife Refuge, Monitoring Year 2000. Patricia Ann Quigley, Inc., Norristown, PA.

Rusello, K., 2006. Wetland Restoration in Urban Settings: Studies of Vegetation and Seed Banks in Restored and Reference Tidal Freshwater Marshes (M.S. thesis). University of Maryland, College Park.

Schmid, J.A., 1994. Wetlands in the urban landscape of the United States. In: Platt, R.H., Rowntree, R.A., Muick, P.C. (Eds.), The Ecological City: Preserving and Restoring Urban Biodiversity. The University of Massachusetts Press, Amherst, pp. 106–133.

Simenstad, C.A., Thom, R.M., 1996. Functional equivalency trajectories of the restored Gog-Le-Hi-Te estuarine wetland. Ecological Applications 6, 38–56.

Simenstad, C., Toft, J., Higgins, H., et al., 2000. Sacramento/San Joaquin Delta Breached Levee Wetland Study (BREACH). University of Washington School of Fisheries, Seattle.

Simpson, R.L., Good, R.E., Leck, M.A., et al., 1983. The ecology of freshwater tidal wetlands. BioScience 33, 255–259.

Sloey, T.M., Willis, J.M., Hester, M.W., 2015. Hydrologic and edaphic constraints on *Schoenoplectus acutus*, *Schoenoplectus californicus*, and *Typha latifolia* in tidal marsh restoration. Restoration Ecology 23, 430–438.

Spieles, D.J., 2005. Vegetation development in created, restored, and enhanced mitigation wetland banks of the United States. Wetlands 25, 51–63.

Stagg, C.L., Krauss, K.W., Cahoon, D.R., et al., 2016. Processes contributing to resilience of coastal wetlands to sea-level rise. Ecosystems 19, 1445–1459.

Stillwater Environmental Services, 2003. Decker Island Phase II Habitat Development and Levee Rehabilitation Project, Initial Study/Mitigated Negative Declaration Public Review Draft. Stillwater Environmental Services, Davis, CA.

Suding, K.N., 2011. Toward an era of restoration in ecology: successes, failures, and opportunities ahead. Annual Review of Ecology, Evolution, and Systematics 42, 465–487.

Sullivan, L.R., 2015. If You Build It, What Will Come? Assessing the Avian Response to Wetland Restoration in the Mississippi River Bird's Foot Delta Through Multiple Measures of Density and Biodiversity (M.S. Thesis). Louisiana State University, Baton Rouge.

Syphax, S.W., Hammerschlag, R.S., 1995. The reconstruction of Kenilworth Marsh, the last tidal marsh in Washington, D.C. Park Science 15, 15–19.

Tanner, C.D., Cordell, J.R., Rubey, J., et al., 2002. Restoration of freshwater intertidal habitat functions at Spencer Island, Everett, Washington. Restoration Ecology 10, 564–576.

Teuchies, J., Jacobs, S., Oosterlee, L., et al., 2013. Role of plants in metal cycling in a tidal wetland: implications for phytoremidiation. The Science of the Total Environment 445–446, 146–154.

USACE (U.S. Army Corps of Engineers), 2017. Louisiana Coastal Wetlands Planning, Protection and Restoration Act. www.lacoast.gov.

US EPA (US Environmental Protection Agency), 1997. An environmental characterization of the District of Columbia – a scientific foundation for setting an environmental agenda. US Environmental Protection Agency – Region 3, Philadelphia, PA.

Van Damme, S., Frank, D., Micky, T., et al., 2009. Tidal exchange between a freshwater tidal marsh and an impacted estuary: the Scheldt estuary, Belgium. Estuarine, Coastal and Shelf Science 85, 197–207.

Vandenbruwaene, W., Maris, T., Cox, T.J.S., et al., 2011. Sedimentation and response to sea-level rise of a restored marsh with reduced tidal exchange: comparison with a natural tidal marsh. Geomorphology 130, 115–126.

Vandenbruwaene, W., Meire, P., Temmerman, S., 2012. Formation and evolution of a tidal channel network within a constructed tidal marsh. Geomorphology 151–152, 114–125.

Verhoeven, J.T.A., Whigham, D.F., van Logtestijn, R., et al., 2001. A comparative study of nitrogen and phosphorus cycling in tidal and non-tidal riverine wetlands. Wetlands 21, 210–222.

Wang, X., Yu, J., Zhou, D., et al., 2012. Vegetative ecological characteristics of restored reed (*Phragmites australis*) wetlands in the Yellow River Delta, China. Environmental Management 49, 325–333.

Weinstein, M.P., Balletto, J.H., Teal, J.M., et al., 1997. Success criteria and adaptive management for a large-scale wetland restoration project. Wetlands Ecology and Management 4, 111–127.

Whigham, D.F., Simpson, R.L., 1992. Annual variation in biomass and production of a tidal freshwater wetland and comparison with other wetland systems. Virginia Journal of Science 43, 5–14.

Whitley, S.N., Bollens, S.M., 2014. Fish assemblages across a vegetation gradient in a restoring tidal freshwater wetland: diets and potential for resource competition. Environmental Biology of Fishes 97, 659–674.

Wilson, R.F., Mitsch, W.J., 1996. Functional assessment of five wetlands constructed to mitigate wetland loss in Ohio, USA. Wetlands 16, 436–451.

Zedler, J.B., 2001. Handbook for Restoring Tidal Wetlands. CRC Press, Boca Raton, FL.

Zedler, J.B., Callaway, J.C., 1999. Tracking wetland restoration: do mitigation sites follow desired trajectories? Restoration Ecology 7, 69–73.

Zhao, Q., Bai, J., Huang, L., et al., 2016. A review of methodologies and success indicators for coastal wetland restoration. Ecological Indicators 60, 442–452.