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Evaluating the progress of engineered tidal wetlands

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Abstract

New terminology is needed for the assessment of wetland restoration projects, focusing on progress towards ecological goals rather than the yes/no alternative of success versus failure. Mitigation projects should be evaluated based on 'compliance' of specific mitigation criteria. Peer-reviewed assessments of wetland restoration projects have focused on appropriate parameters (topographic, hydrologic, soil, vegetation, and animal components); however, for the most part, they have evaluated small, newly restored wetlands over the short-term with little repeated sampling. Future assessments should focus on understanding problems at a particular site by identifying cause–effect mechanisms. We review a case study from San Diego Bay where detailed assessments led to the identification of problems and subsequent management alternatives. We also recommend the use of two novel approaches: experimentation and the evaluation of ecosystem resiliency to unplanned disturbances. These assessments will provide a better understanding of ecosystem functioning and enhance current comparisons of natural and restored systems. A stronger science base for wetland restoration and adaptive management do not guarantee that restoration targets will be reached; however, these approaches will identify the causes of problems and allow us to predict whether or not restoration targets can be reached in a timely manner.

Keywords: Adaptive management; Assessment; Coastal wetlands; Literature review; Mitigation; Salt marshes; Wetland restoration

1. The term 'success'

There is a need to reassess the terminology used to evaluate wetland restoration projects. Several authors who reviewed the status of wetland creation and restoration for the Environmental Protection Agency (Kusler and Kentula, 1989) addressed the issue of project success, but most avoided the term 'failure.' Like many, Lewis (1989a,b) proclaimed several projects successful and listed shortcomings of other projects. Some authors avoided the judgment of failure by projecting into the future. Clewell and Lea (1989) stated, with regard to forested wetlands: 'Most creation projects are still too recent to predict their ultimate success' and, 'There has been an implicit attitude that success criteria will become self-evident, once the planted trees mature.' Likewise, Erwin (1989) had this to say about a freshwater marsh: 'Current trends indicate the wetland is achieving the completion of successful restora-

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tion goals. Continued monitoring will insure the stated specific conditions for the creation of the 8.4 acre wetland are met.' All seem to have struggled with the yes/no aspect of the term 'success.' Fonseca (1989) was the most critical, suggesting in his review of seagrass restoration that 'failures have been masked by improper success criteria, site selection, technique, and monitoring.' Among the peer-reviewed literature on salt marsh restoration sites (see below), only four of 26 papers (Tables 1 and 2) indicated that the projects were successful in creating functioning habitats (Seneca et al., 1976; Lindau and Hossner, 1981; Webb and Newling, 1985; LaSalle et al., 1991). The remaining 22 papers identified shortcomings.

In considering the reintroduction of threatened species, Pavlik (1996) (p. 130) defined success as 'meeting taxon-specific objectives that fulfil the goals of abundance, extent, resilience, and persistence.' However, none of these attributes has a clear target, nor will all assessment protocols necessarily lead to the same conclusions about the chances for achieving self-sustaining populations. Hence, a judgment of 'success' would only be valid for specific objectives, on a particular evaluation date, and for a specific evaluation protocol. Pavlik (1996) goes on to distinguish 'project success' (a broad term which may be achieved by contributing knowledge or new tools) and 'biological success' (based on performance of the target taxon); however, this falls short of clarifying the terminology. Combining technical definitions (as in Pavlik, 1996) with terms that are familiar to the lay public (success, failure) leads to misunderstandings in the assessment arena.

When applied to the assessment of restoration sites, the term 'success' implies that the project has met all of its objectives. The word implies finality and certainty, while the alternative (failure) is likewise definite. More likely, some objectives of a particular restoration project will be achieved and some will not, at least not right away. By the first growing season, plants may be growing well and anticipated to satisfy expectations, but specific targets may not be met. Such a project is not yet a success, nor is it a failure. In general, it is unclear what conditions would lead to a judgment of 'failure.' Hence, the 'all or nothing' terminology seems inappropriate in a restoration context. If no clear distinction can be drawn between a judgment of success or failure, then another term should be substituted.

2. Alternative terminology

More appropriate terminology is needed for restoration efforts, which concern dynamic ecosystems that change over time, are evaluated with various techniques at various times, and may have moving targets (e.g. matching conditions in a reference wetland). For restoration projects that are not undertaken as mitigation, we suggest using the term 'progress' to characterize their status. The target may be a set of specific objectives (e.g. presence of particular species, plant cover, biomass, etc.) or functional equivalency with natural reference habitats. For wetlands, the relevant attributes include hydrologic, water-quality-improvement, and biodiversity-support functions. In addition, the ecosystem should be self-sustainable.

Because of the legal requirement to compensate for damaged habitat, the compensatory mitigation arena is different. A project either does or does not satisfy all the mitigation criteria, and the mitigator either does or does not have to continue working toward compliance. 'Compliance' is the preferred term for achieving thresholds, or standards, for each criterion specified in the mitigation requirements. To call such projects successes or failures without an evaluation of functional integrity or sustainability introduces confusion.

Project proponents understandably want to promote the projects they have undertaken, especially if they are costly. At Batiquitos Lagoon, the $55-million dredging program of the Port of Los Angeles and City of Carlsbad was billed as 'one of the most significant and successful wetlands restoration projects in the United States' in March 1997 (field trip description, conference on 'California and the World Ocean'). For a project that was about 1 year old, this billing seems premature. A judgement of success should be based on long-term assessment and ecosystem functioning. The need to avoid a judgement of 'failure' may lead proponents to ignore problems

Table 1
Monitoring characteristics for single-site evaluations of wetland restoration projects in the peer-reviewed literature

Location	Reference	Size (ha)	Type	Age (years)	Sampling frequency		Parameters evaluated					
					No.	Years	Topo	Sediment/soil	Plants	Inverts	Fish	Birds
East coast												
CT	Sinicrope et al., 1990	20	Dike	10	2	2		×	×			
	Fell et al., 1991	20	Dike	12	1	1				×		
	Peck et al., 1994	20	Dike	13	2	2				×		
VA	Havens et al., 1995	2.2	Excavate	5	2–3	1		×	×	×	×	×
NC	Moy and Levin, 1991	0.24	Excavate	3	5	3		×		×	×	
NC	Levin et al., 1996	0.9	Dredge	5	10	5				×		
NC	Rulifson, 1991	na	Excavate	5	Mo	5					×	
	Craft et al., 1991	2.15	Excavate	3	10	2		×				
Gulf coast												
TX	Lindau and Hossner, 1981	4.5	Dredge	2	4	3		×				
	Webb and Newling, 1985	4.5	Dredge	4	3	5			×			
TX	Minello et al., 1994	8	Dredge	5	3	2				×	×	
Pacific coast												
WA	Shreffler et al., 1990	3.9	Excavate	3	Ext	2					×	
	Shreffler et al., 1992	3.9	Excavate	3	Ext	2					×	
	Simenstad and Thom, 1996	3.9	Excavate	8	Ext	7	×	×	×	×	×	×
OR	Frenkel and Morlan, 1991	32	Dike	10	3–7	11	×	×	×			
CA	Chamberlain and Barnhart, 1993	3.5	Dike	2	Mo	1.3					×	
CA	Langis et al., 1991	4.9	Excavate	4	2–6	2		×				
	Scatolini and Zedler, 1996	4.9	Excavate	4	8	1		×		×		
	Zedler, 1996	4.9	Excavate	10	14	6		×	×	×	×	

Table 2
Monitoring characteristics for multiple-site evaluations of wetland restoration projects in the peer-reviewed literature

Location	Reference	Size (ha)	Multiple sites	Type	Age (years)	Sampling frequency		Parameters evaluated					
						No.	Years	Topo	Sediment/soil	Plants	Inverts	Fish	Birds
NC	Seneca et al., 1976	na	Yes	Dredge	1–5	3	3			×	×		
NC	Craft et al., 1988	na	5	Exc/dredge	1–15	1	1		×				
NC	Sacco et al., 1994	0.1–0.5	6	Exc/dredge	1–17	1	1		×		×		
SC	LaSalle et al., 1991	35	2	Dredge	4 and 8	1	1		×	×	×	×	
TX	Minello and Zimmerman, 1992	5–8	3	Dredge	2–5	1	1			×	×	×	
TX	Minello and Webb, 1997	0.1–10.5	10	Exc/dredge	3–15	2	1				×	×	
CA	Haltiner et al., 1997	4.9 and 7	2	Excavate	5 and 11	7	7	×	×	×		×	

and selectively reveal monitoring data, neither of which is in the interest of improving management or restoration protocols.

Even though mitigators focus on the ultimate judgment of compliance versus noncompliance, we suggest that the progress of mitigation projects be evaluated so that the appropriate agency personnel can predict chances of achieving compliance over time. We agree with Pavlik (1996) that even projects that comply with mitigation criteria may not be fully functional in supporting target species or in sustaining biodiversity (see section on Sweetwater Marsh, below).

3. The peer-reviewed literature on coastal wetland restoration projects

In order to evaluate the types of restoration assessments that have been completed, we located and reviewed papers that presented data from monitoring salt marsh restoration projects. We found 26 such papers, 19 of which concerned single wetland restoration sites (11 sites in all; Table 1); the remaining seven papers described multiple sites, referring to ~ 20 additional sites (Table 2). We excluded agency and consulting reports in our review, since these are harder to locate and are less likely to have undergone peer review. Many of the papers indicated problems in assessing and documenting restoration progress, for a variety of reasons, including: (1) no clear goals were established to determine success; (2) no natural marsh site was used for reference; (3) data only covered short term; and (4) spatial and temporal variability of both natural and restored system was too high to make a clear comparison.

The projects described in the 26 papers included wetlands that were restored or created by excavating uplands (14 papers), using dredge material (10), or removing dikes (5). Most of the projects were small. Some of the 11 single site evaluations were reported in more than one paper. Of these 11 sites, four were <3 ha, four were 3–5 ha, and three were >5 ha. Seven papers (Table 2) evaluated multiple sites (2–10 sites per paper). The papers that described multiple sites covered a broader range, but most of the sites were less than 5 ha (Fig. 1).

For the most part, monitoring has been conducted on newly restored marshes. Fifteen papers evaluated wetlands that were less than 6 years old (Fig. 1). Researchers in North Carolina (Craft et al., 1988; Sacco et al., 1994), South Carolina (LaSalle et al., 1991), Texas (Minello and Zimmerman, 1992; Minello and Webb, 1997), and California (Haltiner et al., 1997) have used assessments of multiple sites of different ages in order to evaluate development over time, with sites ranging in age from 1 to 17 years.

Monitoring was conducted over the short-term, with little repeated sampling (Fig. 1). The majority of the monitoring periods (19 of the 26 papers) were for less than 4 years. Many projects were one-time assessments of a site (5), while others included 2–5 sampling periods (9); only 12 of the 26 papers were based on six or more sampling periods.

Several differences were identified between reference wetlands and restored systems that have been highly modified. Engineered wetlands of North American coasts (those that are created from upland or deep water, and those that have substantial hydrologic or topographic alterations) frequently have significant shortcomings; they may lack the appropriate topographic complexity (Vivian-Smith, in press), have modified tidal regimes, experience unexpected erosion and/or sedimentation (Haltiner et al., 1997), fail to support the desired vegetation, lack sufficient soil organic matter and nutrient supplies (Craft et al., 1988; Langis et al., 1991), fail to support desired animal populations (Moy and Levin, 1991; Sacco et al., 1994; Scatolini and Zedler, 1996; Minello and Webb, 1997), or contain contaminants uncovered during construction. Any of these problems can keep a site from achieving functional equivalency with reference wetlands.

More seriously, predictions that engineered wetlands will follow trajectories aimed at reference wetland ‘targets’ may be unwarranted (Zedler and Callaway, 1999). Although the concept of trajectories has been widely discussed in the literature (Aronson and Le Floc’h, 1996; Hobbs and Norton, 1996; Dobson et al., 1997), supportive data are lacking. The few long-term data sets that characterize wetland development fail to predict functional equivalency within the prescribed monitoring periods (Simenstad and Thom, 1996; Minello and Webb, 1997). Additional studies of the development of restored systems are needed before the path of a wetland restoration project can be predicted. Most importantly, it should not be assumed that time is the only factor that keeps a project from meeting its targets.

4. Attributes used in assessment

Although some studies have looked at multiple components of the ecosystem, most studies (18 of the 26) have focused on only one or two components (Tables 1 and 2). At Barn Island, CT, Galveston Bay, TX, and Sweetwater Marsh, CA, different ecosystem components have been treated in separate papers. An average of 2.9 'components' were evaluated at each of the 11 single sites. Only Simenstad and Thom (1996) and Havens et al. (1995) have reviewed five or more components in a single publication for a particular site. Invertebrate (14 of the 26 papers) and fish (13) populations have been the most commonly studied component at salt marsh restoration projects. Sediments and soils were evaluated 14 times (this includes studies of both vegetated soils and creek sediments for invertebrate populations). Plants were evaluated in 10 of the papers, topography in three, and birds in two of the papers. Within each of these areas, assessments varied widely in terms of methods and frequency.

Soils: Most commonly, organic matter content and texture have been evaluated, both in stud-

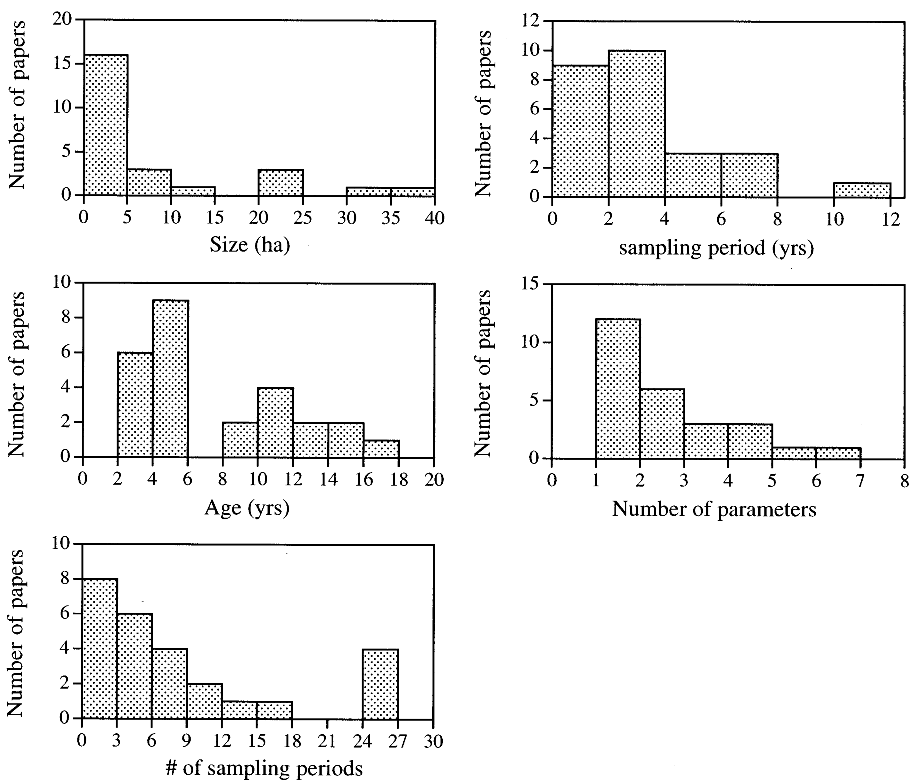

Fig. 1. Monitoring characteristics from peer-reviewed papers that assess wetland restoration projects: size, age of the restoration site, number of sampling periods, length of sampling period, and number of parameters assessed. Data come from 26 papers that evaluated single and multiple sites. Where multiple sites were considered, the largest and oldest sites and the most intensively measured parameters were plotted.

ies of vegetated areas (e.g. Lindau and Hossner, 1981; Craft et al., 1988; Langis et al., 1991) and those related to invertebrate habitats (Moy and Levin, 1991; Sacco et al., 1994). Additionally, for plant studies, total Kjeldahl nitrogen (TKN) was measured in four of five cases where nutrients were considered, with fewer evaluations of porewater constituents (Craft et al., 1991) or soil nutrient processes (N-fixation, Langis et al., 1991).

Plants: Usually plant cover, density, and/or biomass have been measured, with some studies also measuring species number, plant height, and total stem length (as a surrogate for destructive biomass sampling). Only two of the studies have looked at the change in area of different habitat types or vegetation classes.

Invertebrates: Comparisons of invertebrate populations in natural and restored marshes have included infauna (both macro and meiofauna; e.g. Moy and Levin, 1991), epibenthic invertebrates (Levin et al., 1996; Scatolini and Zedler, 1996), and natant macrofauna (Minello et al., 1994). A few studies have focused on individual species of interest (Fell et al., 1991), but more commonly, these comparisons have been a survey of both the community composition and the density of invertebrates in the vegetated wetland, mudflats, and adjacent tidal creeks.

Fish: Fish have been widely studied in restored coastal wetlands, with the focus on describing composition and density of the fish populations. In addition, there have been some studies of gut content (Shreffler et al., 1990; LaSalle et al., 1991; Moy and Levin, 1991; Shreffler et al., 1992), use of creek habitats (Minello et al., 1994), and gear type (Rulifson, 1991). Most studies have found that fish use is relatively high (especially compared to other biological parameters) because fish are mobile enough to move into restored areas quickly.

Birds: Only Havens et al. (1995) and Simenstad and Thom (1996) have evaluated bird use of restored coastal wetlands, despite the fact that bird use of areas is often a goal of projects.

The degree of assessment required for comparing engineered and natural wetlands depends in part on the rationale for the project (e.g. is it a mitigation site?) and the ecological goals. More detailed assessments are required where projects are designed to compensate for damages to natural wetlands. In these cases, the risk of incorrectly judging functional equivalency is high, because a success rating could justify further habitat loss. That is, if inadequate mitigation sites are decreed to be adequate ('false compliance'), the process of mitigation will be used when it is not warranted. More detail is also required if the ecological goals are more specific, for example, where an endangered species is targeted for reintroduction. It is much easier to judge if wetland conditions are present than to decide if regional biodiversity will be sustained in the long term. We recommend that all engineered wetlands have the general goal of supporting regional biota, including (a) attracting the desired species and (b) resisting invasion by exotics. Specific goals will differ for each project, but all projects should aim toward a low-maintenance, self-sustaining ecosystem.

All assessments of progress should go beyond superficial characterizations, in spatial and temporal terms and in the detail of the assessment. An adaptive assessment approach may well be needed, in order to document both the benefits that have developed *and* the problems that remain. Early assessments may suggest additional items to add to the monitoring program or identify attributes that are not useful and may be dropped. For example, trash may accumulate unexpectedly in an urban wetland, indicating the need to document the type of material that is damaging vegetation and allow project managers to identify the source and suggest management actions. In all cases, data need to be analyzed quickly and reviewed regularly. Even the most well-conceived monitoring programs may need to respond to unexpected events (including the finding that existing protocols fail to show any pattern) by expanding or contracting in scope or frequency (Zedler, 1996).

Overall, the assessment protocol should be more than just a checklist and should provide understanding of the problems encountered, that is, it should identify possible cause–effect mechanisms at the restoration site. Armed with such information, managers can attempt corrective action over the course of development of the project. A simple check-list of conditions or data sheet with regularly sampled attributes ('mindless monitoring') may not be responsive to this need. Investigators who are trained to interpret sampling data and identify problems are needed. A San Diego Bay case study (see below) indicates progressive action from problem identification, experimentation to find corrective measures, long-term data to predict time to equivalency with natural wetlands, and an ultimate management decision.

4.1. San Diego Bay case study

The Pacific Estuarine Research Laboratory has monitored the progress of engineered wetland habitats at Sweetwater Marsh National Wildlife Refuge, San Diego Bay, from 1989 to 1997 on an annual basis and, in addition, conducted numerous research projects to identify and understand problems with restoration (Zedler, 1997). Habitat for three endangered species was the target for this mitigation project. At the end of the assessment period, one wetland ($\sim$ 5 ha) was 13 years old; the other ($\sim$ 7 ha) was 8 years old.

Compliance was achieved quickly for the California least tern, for which forage species were required. Large deep channels were constructed and readily occupied by fishes. The standards (75% of the fish species of natural channels and 75% of the fish densities in natural channels) were met within 3 years.

Compliance was achieved for the salt marsh bird's-beak (a hemi-parasitic annual plant) in 1995. The standard in this case was to establish a small population (five patches, each with ≥ 20 plants) near the historical location of a patch that was extirpated in the late 1980s. Self-sustainability was required for 3 years and was defined as stable or increasing numbers of individual plants within each patch. Seeds were collected at nearby Tijuana Estuary and sown within a high-marsh remnant that was surrounded by artificial channels during excavation of the older constructed wetland (this wetland is a series of eight marsh islands). Although plants grew and flowered, few seeds were produced. We suspected pollinator limitation, as the native pollinators are ground-nesting bees, which would not have found suitable supra-tidal habitat on the small constructed islands. The reintroduction project was thus moved to the larger natural wetland, Sweetwater Marsh. Seeds were sown annually through 1992, and assessment for determining compliance began in 1993. The population rose from $\sim$ 5000 plants in 1993 to over 14 000 in 1994 and 1995. Furthermore, the seeds had begun to disperse to additional areas, including some of the constructed habitats.

We recommended that the effort be judged in compliance with the 100-plant standard, even though some individual patches had slightly fewer plants in 1996 than in 1994 (but still well over the 20-plant/patch target). The US Fish and Wildlife Service accepted our recommendation, but population counts were continued for purposes of providing information. The population dropped precipitously to $\sim$ 2000 plants in 1996 (a relatively dry year) and it shrank to two patches that were at lower elevation than the area planted at Sweetwater Marsh. In 1997, plants were again found in the patches monitored for compliance, and the total population numbered $\sim$ 5000 plants. Although this project has achieved compliance and produced far more than the target of 100 plants, the fate of the population is not yet certain. Continuing studies (M. Fellows, PERL, in progress; G. Noe, PERL, in progress) are relating establishment to variations in rainfall and canopy cover.

Compliance has not been achieved for the light-footed clapper rail. Seven home ranges were to be constructed, with each home range having a list of requirements (Fig. 2). Of these requirements, producing tall cordgrass for nesting has been the most difficult to achieve. The research program provided ample explanations for short vegetation — coarse, sandy soil failed to supply or retain adequate nitrogen (Langis et al., 1991; Gibson et al., 1994). Scale-insect outbreaks, which only occurred in constructed wetlands, further limited plant growth (Boyer and Zedler, 1996). Fertilizing with nitrogen produced tall plants (Boyer and Zedler, 1998) but led to species shifts (Boyer and Zedler, 1999).

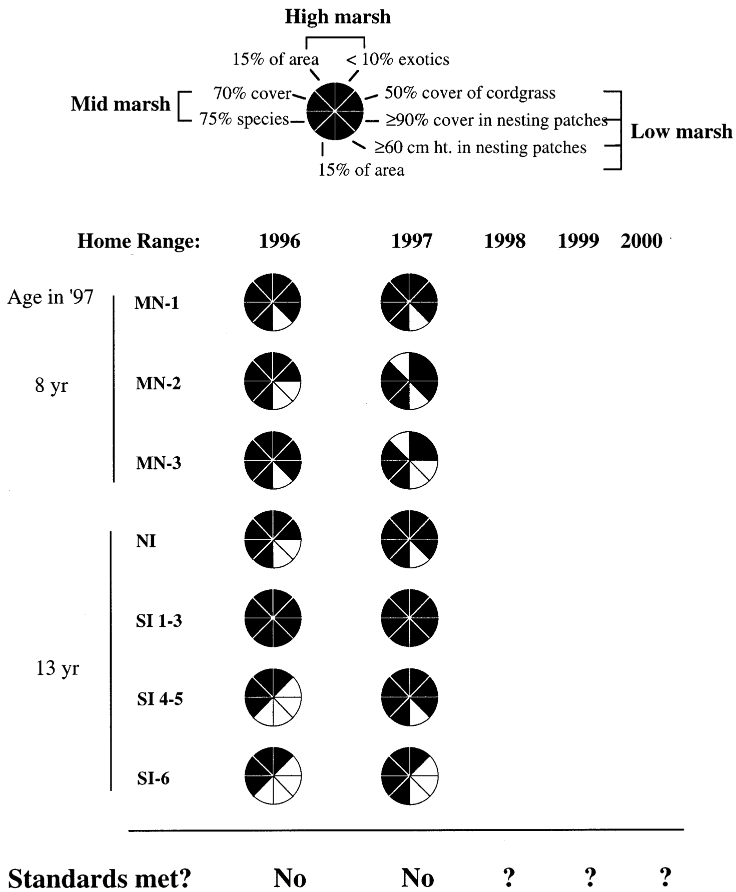

Fig. 2. Progress towards compliance for seven potential light-footed clapper rail home ranges at Sweetwater Marsh National Wildlife Refuge, San Diego. Mitigation standards that were met in 1996 and/or 1997 for the light-footed clapper rail are shown in black. Full compliance required that standards be met for 3 years, hence, the site could not comply before the year 2000. Data collection was terminated in 1997 when an alternative agreement was reached (see text).

The long-term prognosis for the site's ability to support clapper rail nesting is bleak, based on the 10-year monitoring record. Neither soil organic matter content nor TKN is on a short-term trajectory toward levels that are found in nearby natural marshes. Assuming a linear fit between organic matter content over time, we projected that it would be 22 more years before values in natural marshes would be achieved. Organic matter content, however, has been relatively constant in recent years, and a negative exponential equation fits the data with a higher r^2-value. Using this projection into the future, the site would never match reference wetland levels of organic matter. For TKN, the time period for equivalency with natural wetlands would be 40 years (Zedler and Callaway, 1999).

These data and our ecological understanding of factors limiting cordgrass height growth led us to recommend that the mitigation program be terminated with an alternative penalty, namely, restoring additional habitat by removing fill (amount and location to be determined). This advice was accepted, as both the mitigators (California Department of Transportation and US Army Corps of Engineers) and the decision-making agency (US Fish and Wildlife Service) were reluctant to remodel the site (excavating coarse sediments and importing fine sediments) or wait for a miracle. Although we suggested that adding a network of tidal creeks to the younger marsh might enhance cordgrass growth, we also acknowledged that the construction activities might be very damaging to the wetland. Because the constructed marshes serve purposes other than clapper rail nesting (e.g. habitat and foods for other bird species), construction disturbance was not an attractive alternative. In summary, the San Diego Bay mitigation site met two of the three compliance criteria and made progress toward the restoration objectives for the light-footed clapper rail, but it did not comply with the specific mitigation requirements.

5. Novel assessment approaches

In addition to comparisons of restored and natural wetlands, we suggest two novel approaches to the assessment of restoration progress. These approaches will extend our understanding of ecosystem functioning at restoration sites and should be encouraged at as many sites as possible. The first is the use of planned experiments. Manipulative experiments at restoration sites are an important step beyond comparisons of natural and restored systems and will allow for development of new restoration methods as well as insight into ecosystem functioning. At Tijuana River National Estuarine Research Reserve (Tijuana Estuary), we have established a major experiment at a newly excavated restoration site, the Oneonta Tidal Linkage (Fig. 3). The intertidal salt marsh habitat at the site supports 87 experimental plots designed to test the role of plant diversity (number of species) in ecosystem functioning. The experiment will simultaneously allow us to assess the relative ability of eight species to establish and spread, and ultimately, their ability to support wildlife.

A much larger experiment has been planned for the second restoration phase at Tijuana Estuary. This 8-ha ‘Model Marsh’ (Fig. 4) is designed to

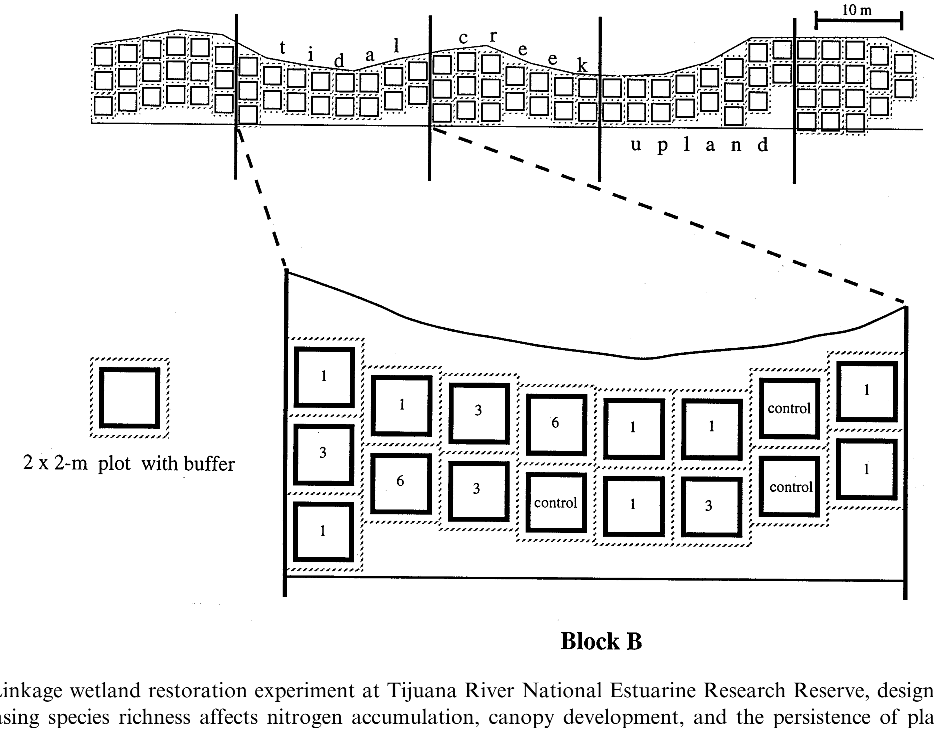

Fig. 3. Tidal Linkage wetland restoration experiment at Tijuana River National Estuarine Research Reserve, designed to determine whether increasing species richness affects nitrogen accumulation, canopy development, and the persistence of plant assemblages. Upper diagram shows the arrangement of 2 × 2 m experimental plots in five blocks, and the inset shows the layout of plots within a block, including control, one-, three-, and six-species plots.

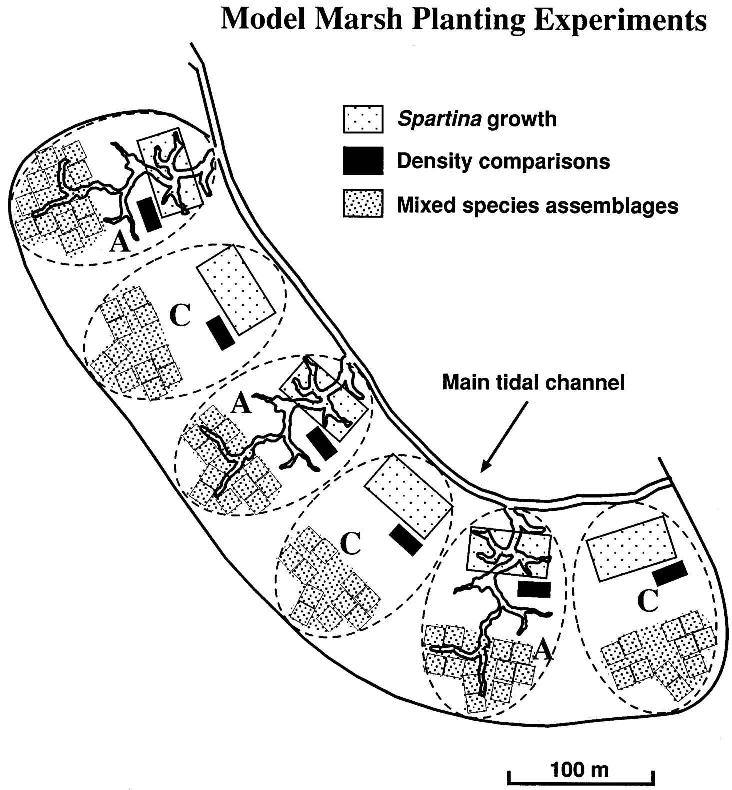

Fig. 4. Proposed model marsh, at Tijuana River National Estuarine Research Reserve. Restoration project will include replicate areas with and without a network of tidal channels, as well as smaller experiments designed to test substrate amendments and other planting techniques.

improve tidal flushing, provide habitat, and support research on ecosystem restoration. The main variable to be manipulated at this experimental site is the presence or absence of a tidal creek network. Three replicate areas (1.3 ha each) will be constructed with tidal creeks and three without. Whole-ecosystem responses will be assessed within this site, ranging from microbial activity to fish and bird use. We anticipate more rapid habitat development and greater wildlife use where tidal creeks are present. The Model Marsh will also incorporate several smaller experiments that will assess restoration progress with different substrate, type of plant species, and density of planting.

The situations where experimentation is useful may be limited, but our experience suggests that many of the shortcomings of restoration projects are readily addressed through experimentation in restoration sites. At present, we are comparing the growth of halophytes in sediment that is coarse, clay-amended, and kelp-amended at Tijuana Estuary. Inadequate nitrogen-supply functions were identified by adding nutrients to engineered and natural wetlands at San Diego Bay; cordgrass showed a response in the constructed salt marsh, but not in the natural marsh (Boyer and Zedler, 1998).

The second novel approach we recommend is the evaluation of ecosystem responses to unplanned disturbance events. For example, a recent algal bloom at the Oneonta Tidal Linkage allowed us to assess the resilience of different species and assemblages to smothering by *Enteromorpha* and *Ulva* species. Other typical unplanned disturbances at restoration sites include herbivory, sedimentation and erosion events, exotic species invasions, and drought. Planted salt marsh vegetation is susceptible to invasion except when soils are saline, as shown in tidal wetland mesocosms (Callaway et al., 1997). Exotic plant invasions occur readily where soil salinities are lowered by freshwater treatments. Sites with excess freshwater inflow can expect greater problems with invasive exotics. Because the goal of restoration projects is to create sustainable ecosystems over the long term, observing ecosystem responses to either planned or unplanned perturbations can provide insights into the ecosystem's resilience and recovery mechanisms.

Inability to resist or recover from disturbances can also be detected by simultaneously assessing the degree of change in, and the responses of, engineered and natural wetlands. A mitigator need not be required to construct a wetland that is free of disturbance; rather, the engineered system should be as resilient to the disturbance as a reference wetland. We suggest tests for engineered and natural wetlands that would uncover shortcomings in functioning, e.g. experiments with nutrient loading (to determine growth-limiting factors), and we suggest observations of wetland responses to invasive species and flooding (e.g. impacts of erosion and sedimentation events). While we have several ideas about the utility of this approach, we have not found examples in the restoration literature.

6. Adaptive management

Restoring and creating coastal wetland habitat is not yet a predictable process. Hence we recommend that research be built into the restoration site and the assessment program. Then, when problems arise, it will be possible to find solutions. Among the shortcomings of coastal restoration sites are inappropriate locations and excessive sedimentation (Simenstad and Thom, 1996), excessive erosion (Haltiner et al., 1997), improper sediment texture (Langis et al., 1991), insufficient nutrient and organic matter (Craft et al., 1988; Langis et al., 1991), and inadequate 'edge' (Minello et al., 1994). Not enough attention is paid to the complexity of natural coastal wetlands, with the result that restoration sites often have artificial shapes and channel configurations (Zedler et al., 1997). The topographic heterogeneity afforded by dense tidal creek networks is very important to fish (Desmond et al., 2000) and plants (Zedler et al., 1999).

Without studies of the cause–effect relationships between the biotic and abiotic components of restoration sites, we cannot prescribe with confidence the necessary corrective measures. In our case study, the combined research and assessment program generated a tool for accelerating plant growth, i.e. biweekly nitrogen addition. However, a 3-year experiment with nitrogen additions has shown that this tool is not a long-term solution, because species composition can shift toward an annual plant species (Boyer and Zedler, 1999). Ten years of monitoring soil conditions further suggest that the substrate will not be able to sustain tall cordgrass for clapper rail nesting for several decades. The scientific information was used to terminate what had become a futile effort. It is also being used to design future restoration sites that are more likely to attract rails to nest. Incorporated into new designs (e.g. the Model Marsh at Tijuana Estuary) are the following: dense tidal creek networks, over excavation of coarse sediments and importation of fine material, and amendment of substrates with an organic (kelp by-product) supplement.

The entire Tijuana Estuary Restoration Plan is designed as an adaptive management program (Entrix et al., 1991), with several modules making up the ultimate 200-ha excavation. Information gained from construction of each module will be used to improve procedures in subsequent models. The initial research-intensive stage is made possible by the availability of a research laboratory (PERL) with funding for restoration studies, as well as the support of a NOAA National Estuarine Research Reserve. While all restoration programs may not be able to incorporate as much research, it is still possible to design sites with replicate units and to invite scientific studies. A major constraint for environmental scientists is finding locations where research is welcome, where different treatments can be set up in replicate, and where instruments can be used in situ, without vandalism. We commend the NOAA NERR program for helping to fulfill these needs.

7. Recommendations

7.1. Terminology

We recommend that the terms *success* and *failure* be replaced with *progress*, which can be measured in degrees (good, mediocre, poor). *Compliance* should be used to indicate that mitigation criteria have been met.

7.2. Parameters

We recommend assessing topographic, hydrologic, soil, vegetation, and animal components. Topography and hydrology are interdependent, and together these physical features determine the character of the wetland. If simple land forms are constructed (e.g. a square excavation), the site will have low topographic complexity and fewer microhabitats. If tidal water inflow or outflow is impaired, the full range of hydrologic conditions may be lacking. If soils are derived from coarse material, nutrient retention functions may be impaired. If the native plants and animals are not able to survive on the site, and/or if nonindigenous species invade, the wetland will not support regional biodiversity; instead, it may encourage the spread of exotics.

As indicated above, a simple checklist is not appropriate; assessment should be guided by the ecological goals of a project and an adaptive approach. Depending on the particular site, several metrics that are useful are: soil TKN, soil organic matter, soil texture, soil salinity (all within the top 10 cm); canopy architecture (e.g. height histograms) for bird nesting; vegetation cover from low-elevation remote sensing imagery; abundances of invertebrates that are important foods (e.g. crabs for clapper rails); fish species richness and dominance; size distributions of fish within specific habitat types (different tidal creek orders); gut contents to document foods; nesting and production of fledglings by target bird species.

Individual species of plants need to be tracked in reintroduction projects. Pavlik (1996) lists 13 proximal objectives and 10 distal objectives for evaluating reintroductions of endangered plant taxa. Readers are referred to his detailed Table 6-1, which is an excellent check-list for assessing the recovery of target plant species. Two of his general attributes for evaluating reintroductions pertain to whole-system restoration: resilience (ability to recover from perturbation) and persistence (the result of resilience through time). A similar approach was recommended by PERL (1990).

7.3. Evaluation of monitoring record

Wetlands differ in their ability to perform basic functions (improve water quality, reduce flood damage, support food webs), but all provide habitat for plants and animals. To ensure support of biodiversity in the long term, functional attributes of engineered wetlands should: (a) demonstrate the potential for convergence with those of natural wetlands and (b) display stabilizing mechanisms (resistance to, or rapid recovery from, perturbations) similar to those of reference systems. The assessment program should be tailored to the objectives of the project and the site-specific habitat types, incorporating appropriate observations and tests to determine how the topography, hydrology, soils, vegetation, and fauna function in relation to reference systems.

7.4. Role of research

Finally, we recommend that research be incorporated into restoration planning, implementation, and assessment. A stronger science base, and a conscientious effort to incorporate science, are the hope for the future. At Tijuana Estuary and at San Diego Bay, we use restoration sites to facilitate research, while at the same time using research to improve restoration. While these adaptive management efforts do not guarantee that restoration targets will be reached, the approach identifies the causes of various problems and allows us to predict whether or not the target can be reached in a timely manner. In southern

California, where only a tiny fraction of the native coastal wetland habitat remains and where restoration sites are highly urbanized, restoration efforts are less likely to progress at maximum pace unless research is an integral part of the program. In all cases, the incorporation of research into restoration projects will allow for faster development of successful restoration methods, better assessment methods, and better understanding of the functioning of restored systems.

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