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Analytic Methods for Establishing Restoration Trajectories

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Under Ecosystem Function and Restoration Success in Restored Marshes Work Unit

Abstract

This special report identifies metrics (standard and novel) and analytic approaches to developing trajectories and then describes the conceptual process of using those metrics and approaches to develop restoration trajectories to inform adaptive management in salt-marsh systems. We identify the composite time series trajectory (CTST) approach, in which metrics are measured from restoration sites of different ages within a small spatial range, and the retrospective single-site trajectory (RSST) approach, in which the same restoration metrics are measured over time at one restoration site. In all, we assessed the metrics of 39 studies of salt-marsh restoration in the United States between 1991 and 2019.

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Preface

This research was supported in part by an appointment to the Research Participation Program at US Army Engineer Research and Development Center (ERDC)–Coastal and Hydraulics Laboratory (ERDC-CHL) administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the US Department of Energy and ERDC. This study was conducted for the Environmental Management and Restoration Research Program (EMRRP) under work unit “Ecosystem function and restoration success in restored marshes – evaluation trajectories through retrospective and current case studies”.

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1 Introduction

1.1 Background

Coastal salt marshes are among the most important and imperiled ecosystems in the world (Kirwan and Megonigal 2013; Pendleton et al. 2012). Vital not only for habitat and primary productivity, coastal salt marshes protect coastal communities from storm hazards, sustain commercial fisheries populations, and support a diverse recreation economy (Dahl and Stedman 2013). Over the last century, approximately 50% of coastal wetlands have been lost because of direct conversion, and remaining marshes are highly vulnerable to sea level rise, actively degrading in many areas (Gabler et al. 2017; Watson, Raposa, et al. 2017; Watson, Wigand, et al. 2017) or predicted to degrade over the next several decades (Thorne et al. 2016; Thorne et al. 2018; Roman 2017).

As a result, efforts in the Gulf, East, and West Coasts of the United States actively pursued restoration of coastal marshes using dredged material in an effort to reverse these losses (VanZomeren, Murray, and Acevedo-Mackey 2019; CPRAL 2017; Garvey and Brodeur 2016). However, determining the success of those restoration projects presents an ongoing challenge.

Many conceptual models of the progression of a restoration site through time, or *restoration trajectory*, have been proposed (Dobson, Bradshaw, and Baker 1997; Hobbs and Mooney 1993; Hughes, Colston, and Mountford 2005; Langman et al. 2012; Magnuson et al. 1980). Given that interpretations of restoration trajectories are based on which ecosystem attributes are being tracked (for example, ecosystem health, structure, and function), the trajectories are themselves a simplified model, indicating a general direction and approximate endpoint of the restoration effort (Langman et al. 2012). Applying the restoration trajectory concept often involves evaluating multiple trajectories for individual parameters and often incorporates indicator species' presence or abundance as a primary metric. Single parameters can show variable responses to stressors over time (or space), resulting in inconclusive restoration trajectories (Odum, Odum, and Odum 1995; Zedler and Callaway 1999). Alternatively, aggregating parameters to create one trajectory has also had mixed results (SER 2004). Langman et al. (2012) suggest that an ideal trajectory would integrate disparate data that describe site condition and provide information to guide adaptive management of the restoration project.

These different trajectory models use a number of monitoring methodologies. In reviewing the current literature, two broad categories of restoration trajectory monitoring emerge. We have designated these the composite time series trajectory (CTST) approach, in which metrics are measured from restoration sites of different ages within a small spatial range, and the retrospective single-site trajectory (RSST) approach, in which the same restoration metrics are measured over time at one restoration site. The difference in these two categories lies in the presence of additional sites and the time line in which they are assessed, as described in more detail in Section 2.1.

1.2 Objectives

Salt-marsh restoration may involve significant investment and require precise planning and adaptive management to develop resilient ecosystems. A restoration trajectory analysis can help managers assess performance of an ecosystem along the time line of its restoration. Understanding the trajectory of ecosystem restoration projects can improve project planning, management, and performance and allows for adaptive management. To assess the trajectory of restoration in a specific project, project managers must have a grasp on the state of the science and advances in measuring and calculating these trajectories. An understanding of useful metrics and common trajectory assessment methods can help to improve restoration techniques and compare projects. This special report identifies metrics (standard and novel) and analytic approaches to developing trajectories and then describes the conceptual process of using them to develop restoration trajectories that inform adaptive management in salt-marsh systems.

1.3 Approach

A review of the restoration trajectory literature highlights common metrics used to develop salt marsh restoration trajectories (Table 1). While this literature review is not an exhaustive list of metrics or studies, it assesses metrics from 39 studies of salt marsh restoration trajectory in the United States between 1991 and 2019 (Table 1). In these studies, drainage area, vegetation cover, microhabitat, and sediment organic content were the most commonly included metrics. These metrics are common because they are easy to measure, offer predictions about the environment (drainage area), or detail responses to restoration activities (organic matter and vegetation cover). Though they alone do not tell the full story, they help examine restoration progress. Metrics such as stable isotope values and bird diversity were used less often. This decreased frequency may be due to these being site-specific goals or accessibility. For example, if the goal of a wetland restoration project is to provide waterfowl habitat, it would be appropriate to prioritize that metric and others that support the goal. While the presence of birds may indicate a healthy environment, more direct and stable measures of environmental health indicative of natural structure, function of processes based on pre-disturbance, or target reference conditions may be better suited in many situations. Certain metrics may be cost or time prohibitive, such as isotope analysis.

2 Review of Studies

Metrics in Table 1 are placed into categories describing the response of flora, fauna, water quality, and the physical environment. Though metrics from separate categories may be related, a variety of metrics from different categories should be used to holistically investigate the marsh's response to restoration. For example, sediment organic carbon is a physical parameter describing the soil or sediment composition but is directly related to the flora of the system, because soil organic matter is primarily created through the breakdown of plant material. Sediment organic carbon may also be influenced by hydrology and a number of floral metrics, including vegetation cover, diversity, and root-to-shoot ratio. The presence of organic carbon in sediment, living biomass, and detritus suggests the cycling of carbon within those compartments of the ecosystem, without directly measuring fluxes. The influence of metrics on one another necessitates the use of a number of parameters, even if related, for a more comprehensive understanding of the system. Using multiple parameters not only offers greater insight into the condition or characteristics of the marsh but also its function.

Physical metrics can be measured with a range of different monitoring strategies and can vary from remote-based geographic information system (GIS) analysis to physical measurements of soil characteristics in the field and laboratory. Many physical metrics may not be sensitive to restoration actions, such as drainage area and stream order. Other physical metrics may change through the life of the project but can be measured less regularly, such as hydrology and sediment composition. A measurable change in these less-sensitive metrics can indicate significant progress along a restoration trajectory.

Floral, faunal, and water-quality metrics are primarily field and laboratory based and exhibit higher sensitivity to restoration activities and annual and seasonal variation. Often, seasonality may affect results, so monitoring should be done during similar conditions over multiple years. Annual vegetation growth can be very sensitive to changing conditions, so floral metrics (for example, stem density, root-to-shoot ratio) provide an opportunity to measure reactions to restoration activities in the short term (few years). Another advantage to some floral metrics, such as vegetation cover and diversity, is the relatively rapid nature of field data collection. The generally low floristic diversity in salt marshes, and particularly in restored sites, may allow these metrics to be collected with minimal staff training.

Additional novel metrics that were not present in the literature review but may offer value in assessing wetland trajectory include remote sensing of vegetation stage, presence of algal mats, and presence of certain parasites, such as diagenetic trematodes. Remote sensing includes a broad range of metrics that aim to gain information about a site without physically accessing it; data can be acquired using satellites, digital imagery, or other remote means. Remote methods can be used in assessing vegetation cover and, in some situations, diversity. A growing application for remote sensing in the restoration trajectory realm is to assess plant phenophase using digital image time series (O'Connell, Alber, and Pennings 2020). Understanding vegetation temporal dynamics, such as the time spent in each life-cycle stage, may then make responses seen in metrics focused on soil, vegetation, and hydrology more clear. The presence or absence of various species can serve as a higher-level response, as these species may only be present in favorable habitat conditions. Algal mats may indicate a high water-residence time and nutrient levels or severe pollution, typically associated with poor habitat for target species (Barth 2003; Smith 2003). Trematode parasite presence, alternatively, can indicate a strong food web, because the trematodes rely on multiple host species (vertebrate and invertebrates) at different stages in their life cycle. The presence of the parasite thus implies the presence of numerous other (host) species with only low monitoring effort required (Huspeni and Lafferty 2004). As such, this metric's presence would not be expected until a marsh was quite mature—perhaps not providing an early indication that a site is on an appropriate trajectory but rather showing that it had reached a complexity commensurate with reference marshes.

It is critical to choose a suite of metrics that will help assess the restoration goals specific to the project at hand. For example, projects with specific goals such as improvement of waterfowl habitat or water quality via nutrient reduction might include additional metrics to determine progress towards those goals. It is also important to consider the project team's capabilities in terms of labor, expertise, and cost of data collection and processing when choosing metrics. Metrics may be field, laboratory, or computer intensive, and a combination of these approaches will produce more robust restoration trajectories. All US Army Corps of Engineers (USACE) monitoring activities should be accompanied by a monitoring and adaptive management plan as required by USACE policy and guidance.

Table 1. Common metrics used to assess salt-marsh restoration determined from a review of 39 studies. The most common unit for each metric is reported. Each metric is categorized as a physical, floral, faunal, or water-quality parameter.*

Metric	Unit	Category	Percent studies surveyed
Drainage area	ha	Physical	67
Vegetation cover	%, ha	Floral	49
Marsh zone microhabitat	%, ha	Faunal	44
Sediment particulate organic matter content	Particulate organic matter (POM), g/m^3	Physical	36
Vegetation diversity	Species richness, diversity, importance value	Floral	33
Water quality	Salinity, temperature, dissolved oxygen, turbidity	Water quality	33
Benthic macrofauna	*n*, g/m^2, diversity index	Faunal	31
Macrophyte aboveground biomass	g/m^2	Floral	31
Nekton (nonfish)	n/m^3, g/m^3, diversity index	Faunal	31
Fish	g/m^2, n/m^2, diversity index	Faunal	28
Hydroperiod or hydrology	%, h, tidal range	Physical	28
Surface topology	Elevation profile, surface elevation table (SET)	Physical	28
Stem density	n/m^2	Floral	26
Creek surface area	%, ha	Physical	21
Flats surface area	%, ha	Physical	21
Pond surface area	%, ha	Physical	21
Sediment inorganic nitrogen	Total nitrogen soil, %	Physical	21
Stem height	cm	Floral	21
Root biomass	g/m^3	Floral	18
Sediment organic carbon	organic carbon, g $carbon/m^3$	Physical	18
Soil bulk density	g/m^3	Physical	18

* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

Metric	Unit	Category	Percent studies surveyed
Channel order	n	Physical	16
Sediment particle size	mm	Physical	15
Drainage density	m/ha	Physical	13
Net primary production (macrophytes)	net primary production, g carbon/m^2, t	Floral	13
Sediment accretion	g/m^2, t	Physical	13
Sediment composition	%	Physical	13
Sediment phosphorous	phosphorus, %	Physical	13
Sediment total Kjeldahl nitrogen (TKN)	TKN soil, %	Physical	13
Benthic algae biomass	Chlorophyll a, g/m^2	Floral	10
Birds	*n*/m^2, diversity index, nesting	Faunal	10
Consumer stable isotope values	δ13C, δ15N, δ34S	Faunal	10
Primary producer stable isotope values	δ13C, δ15N, δ34S	Floral	10
Gross production (algae)	mg carbon/m^2, t	Floral	8
Stream length	m	Physical	8
Bifurcation ratios	*n*/*N*	Physical	5
Root-to-shoot ratio	g/g	Floral	5

2.1 Trajectory types and analysis

The most basic trajectory is one with just two endpoints: the new, likely bare restoration site and a reference site of nearby mature, natural marsh with similar hydrology, geomorphology, climate, salinity, and other abiotic factors. A reference site is often assumed to represent the endpoint or target of restoration site development and is therefore used to set restoration goals, inform restoration design, and establish success criteria. Such reference sites are also used when creating more detailed trajectories, anchoring the mature end of the time series and representing the conditions of many metrics in that mature state. Considering that restoration projects often occur in areas where native marshes are in decline, care must be taken to select reference sites that are not actively degrading because of stressors from sea level rise or other factors. Otherwise, the mature marsh conditions might not actually represent restoration goals, and the trajectories will become skewed toward a degrading state as compared with desired, stable restoration site development. Degrading marshes can be subject to drowning, which shifts biotic metrics toward more inundation-tolerant species and affects biomass (Nyman and DeLaune 1999; Kirwan and Megonigal 2013). Alternatively, increased erosion of a native marsh edge may eliminate low marsh and create an abrupt transition between midmarsh and open water (Heberger et al. 2009; Reed 2002). Hence, the selection of the *undisturbed natural marsh*, as reference areas are often described, is more challenging now that it has been in the past. However, because reference sites serve as an anchor for one end of the trajectory, they are still of vital importance.

In analyzing restoration trajectories, the analytical methods used range as broadly as the metrics collected. Typically, a restoration site is evaluated through a statistical analysis using selected metrics to develop a trajectory score or comparison. Analysis type depends on the study structure, including number and condition of sites, metrics assessed, and restoration goals of the project. While statistical methods can become very specific, a few broad strategies exist and are outlined in Sections 2.1.1and 2.1.2.

A number of analytical techniques can evaluate and combine information from the various metrics to develop and assess trajectories. To understand and summarize the analysis methods used to turn data on marsh metrics into restoration trajectories, a review of 24 restoration trajectory studies was completed. A summary of representative studies, the method of restoration trajectory developed (CTST or RSST), and statistical approach for trajectory development are included in Table 2.

2.1.1 Composite time series trajectory (CTST) method

The CTST method involves comparing snapshots of multiple similar restoration sites of varying ages, including appropriate reference, to assess a developmental trajectory. The level of similarity to reference and other restoration sites, as assessed through the metrics selected, can inform managers about the progress of the restoration site. This progress may not be linear, so an increased number of restored and reference sites can improve the assessment. A habitat score or similar result may be generated to easily communicate progress. Low-variation metrics may be preferred within this method to avoid results that are not representative of average conditions. That is, ideal metrics would be sensitive to restoration activities but less sensitive to differences between restoration sites such as microclimate or size.

In selecting sites for a CTST analysis, a range of project ages from new sediment placement to the oldest restoration sites available are combined with representatives of mature, natural reference marsh to create the time series. To effectively compare and reduce external variation, comparison restoration or reference sites should have similar geographical, hydrological, and biological settings. Presumably, given similar site characteristics and restoration activities, older sites will have become more similar to a natural ecosystem. Often, multiple sites within a watershed are restored in one large-scale effort, creating opportunities for comparison. A suitable reference site may be nearby but have avoided degradation from development, a disaster event, or chronic stress from climate change. Set-aside or control sites may also be used; these are locations that were degraded similarly to a restoration site but were not restored. These sites can provide a baseline for how the environment may have fared over seasonal and longer-term scale without restoration activities. The CTST method is appropriate when projects do not have pre- and postevent data or are limited in the length of available data.

2.1.2 Retrospective single-site trajectory (RSST) method

The RSST method uses a long-term data set at a single site to measure trajectory. Ideally, data will be available before the site became degraded and managers will also understand the restored state (that is, there will be enough data collected over time from predisturbance through important restoration milestones for managers to be familiar with and interpret site data). Alternatively, progress can be assessed against baseline (degraded) or reference conditions, or both. Research areas that are degraded in a short span of time from a single or series of events may have data pre- and postevent, allowing for a direct comparison with the former environment. Examples of such events include natural and anthropogenic disasters such as a storm or oil spill. The frequency of sampling can influence the trajectory analysis methods available. While more data generate more analysis opportunities, sampling may be done strategically under limited resources or time lines. In addition, if long data sets from RSST sites are driven primarily by regulatory rather than scientific requirements, methods may change to less intensive or less frequent surveys as marshes become established and permit requirements are met, complicating potential analyses.

2.1.3 Comparing CTST with RSST

While the snapshot sampling within the CTST method may involve a single or few sampling events per site, a time-series sampling method (RSST) uses regular repeated sampling to assess progress at a site. The resolution may vary from coarse (annual) to very fine (instantaneous). Generally, a long-term sampling strategy can provide the most information, as projects may take years or decades to fulfill restoration goals. Because of effort requirements, long-term sampling is generally coarse. Resolutions may be mixed in a sampling strategy: for example, daily or hourly measurements may be collected for a short time (week or month) each year in an attempt to account for the effect of short-term variability on the data set.

For both CTST and RSST approaches, a common practice for assessing restoration trajectory is to develop a set of metrics that can represent larger ecosystem functions. High variability in the data of natural systems, both spatially and temporally, can burden monitoring programs by requiring numerous metrics to be regularly collected (Odum, Odum, and Odum 1995; Zedler and Callaway 1999). Given the need to effectively monitor with limited resources, multimetric indices have been proposed to improve efficiency in data collection (Karr 1981; Langman et al. 2012). These indices aim to categorize metrics and encompass a wide range of ecosystem functions by proposing a limited set of disparate yet comprehensive attributes. Metrics within these attributes may be selected according to site-specific characteristics, feasibility, and sensitivity. In 2004, the Society for Ecological Restoration (SER) proposed and Langman et al. (2012, 825) summarized nine attributes: intact community structure, presence of invasive species, presence and condition of key functional groups, physical environment to support biota, normal ecosystem function and development, integration into landscape, no threats to adjacent systems, resistance and resilience, and self-sustaining status (SER 2004, 3–4). According to the Langman et al. method (2012), metrics within these attributes may be rescaled to develop a score on which the ecosystem can be judged relative to a restored condition or reference site. Filtering of metrics may be necessary to remove those deemed ineffective because of limited data range, poor response to disturbance, or a low signal-to-noise ratio. Once categorized, redundant metrics are evaluated, and a single metric per attribute is selected.

Once data are collected and prepared, a number of methods exist for statistical analysis. Hypothesis testing through the comparison of means and regressions are popular methods, but others—including some developed specifically for individual projects—exist. Tests to compare means of data include t tests, ANOVA (analysis of variance), their nonparametric alternatives, and others. Because of their simplicity and applicability to compare the means and variance between two predictor variables, t tests are popular. The result of a t test is a ratio that serves to compare signal-to-noise measurements of the two means, titled a t value. ANOVA allows for the testing of differences between means of two or more groups and can compare data between numerous sites. ANOVAs can be expanded to include multiple independent variables: a two-way ANOVA refers to an ANOVA test with two independent variables. An ANOVA produces a similar test statistic: F. Both t and F values help describe the statistical significance between the variation around the means. Linear regressions model the relationship between data and attempt to fit a linear equation between an independent and dependent variable. Outputs of a linear regression analysis are the linear equation describing the relationship between the independent and dependent variables and the coefficient of determination, which explains what portion of the variation of the dependent variable can be explained by the independent variable. The number and type of data sets and knowledge desired will influence which type of statistical analysis is appropriate for a study. Studies that include measurements of multiple parameters through time will require more complex analytical approaches such as ANOVAs and regressions, while methods such as *t* tests may be appropriate for comparisons of individual parameters.

A subset (23/39, 59%) of the studies from the literature review are presented in Table 2 to describe the restoration trajectory and statistical techniques discussed. The 23 studies in Table 2 range in publication date from 1997 to 2019. Studies are assigned a CTST or RSST descriptor, or both, according to the methods used in the study. Statistical tests used by the studies describe both data examination and analysis methods. In general, in the late 1990s and early 2000s, many studies relied on ANOVA and linear regression. As nonparametric and multivariate techniques became more readily accessible (through software packages such as Plymouth Routines In Multivariate Ecological Research (PRIMER-e); Quest Research, Auckland, New Zealand), these techniques—analysis of similarities, (ANOSIM), similarity percentage (SIMPER), and permutational ANOVA (PERMANOVA), for example—began to be used in conjunction with other analyses. More recently, the complexity of regression models and approaches used for trajectory analysis has increased (for example, ordination regression, quantile regression, meta-analysis). Analytical approach did not correlate to type of restoration trajectory (CTST and RSST); both types were analyzed using the array of techniques described.

As shown in Tables 1 and 2, CTST and RSST methods each occur throughout the time frame of studies considered. RSST approaches are often combined with CTST, because high-quality, long-term data sets are uncommon and may not align with publication time lines. In these instances, short time series of data at multiple sites are used to compare among restored or reference sites. CTST studies are common because of their ability to analyze sites over a short period of data collection.

The statistical methods used ranged from standard (mean, standard deviation) to different types of regressions and specially developed techniques. Methods have generally expanded in variety and become more complex in time as analysis programs have become more accessible.

A recent trend in the literature also includes more specially developed methods as researchers create and propose their method as a universal analysis. Standard, regression, and hypothesis tests (*t* tests) are common methods used to quantify restoration trajectories, while specially developed methods in combination with other well-established statistics, such as effect size and response ratios, are more common in recent approaches.

Table 2. Description of restoration trajectory literature. (NMDS—nonmetric multidimensional scaling.)

Reference	Location	Method	Method details	Trajectory statistics
Minello and Webb 1997	Galveston, TX	CTST	Compared density of nekton and infauna in 10 created marshes (3–15 years in age) to 5 natural marshes to test functional equivalence.	Standard, ANOVA, linear regression
Posey, Alphin, and Powell 1997	Winyah Bay, SC	CTST	Compared created marsh stands ranging in age from 1 to 2 years to 50 years since creation for vegetation and benthos.	Standard, ANVOA, chi square
Weinstein et al. 1996	Delaware Bay, NJ	CTST, RSST	Developed composite criterion [Habitat Value Score] for restoration success based on range of parameters including vegetative cover, measured through historical aerial photography.	Standard, habitat value score / equivalence index
Craft et al. 1999	Outer Banks, NC	CTST, RSST	Compared multiple time-point measures of salt-marsh structure (vegetation, benthic invertebrates) and function (nutrients), at two paired sets of created and natural marshes.	Standard, regression, *t* test
Zedler and Callaway 1999	San Diego Bay, CA	CTST, RSST	Assessed relativized comparisons (created and natural) of four soil and vegetation characteristics.	Equivalence comparison, standard, regression, predicted expected time to equivalence
Boyer, Callaway, and Zedler 2000	San Diego Bay, CA	CTST, RSST	Assessed above- and belowground N storage of marshes created 5 and 10 years ago as compared to reference marsh.	Standard, regression
Craft 2000	NC	CTST, RSST	Assessed nutrient and benthic inverts across created marshes of different ages and within marshes between years.	Standard, regression, *t* test
Short et al. 2000	Great Bay Estuary, NH	CTST	Developed measure of success criteria for eelgrass, salt-marsh, and mud-flat restoration.	Success criteria
Zedler and Callaway 2000	San Diego Bay, CA	CTST, RSST	Performed literature survey and synthesis of parameters measured while monitoring success of salt-marsh restorations. Case study focused on Sweetwater Marsh San Diego Bay.	Standard, regression
Craft, Broome, and Campbell 2002	Aurora, NC	RSST	Compared vegetation and soil development in created and natural marshes over 15-year timespan. Calculated rates of change in parameters.	Standard, ANOVA, regression
Morgan and Short 2002	ME, NH	CTST	Compared four marsh functions across created marshes ranging 1 to 14 years in age and 11 reference marshes.	Standard, principal component analysis (PCA; reference selection), regression

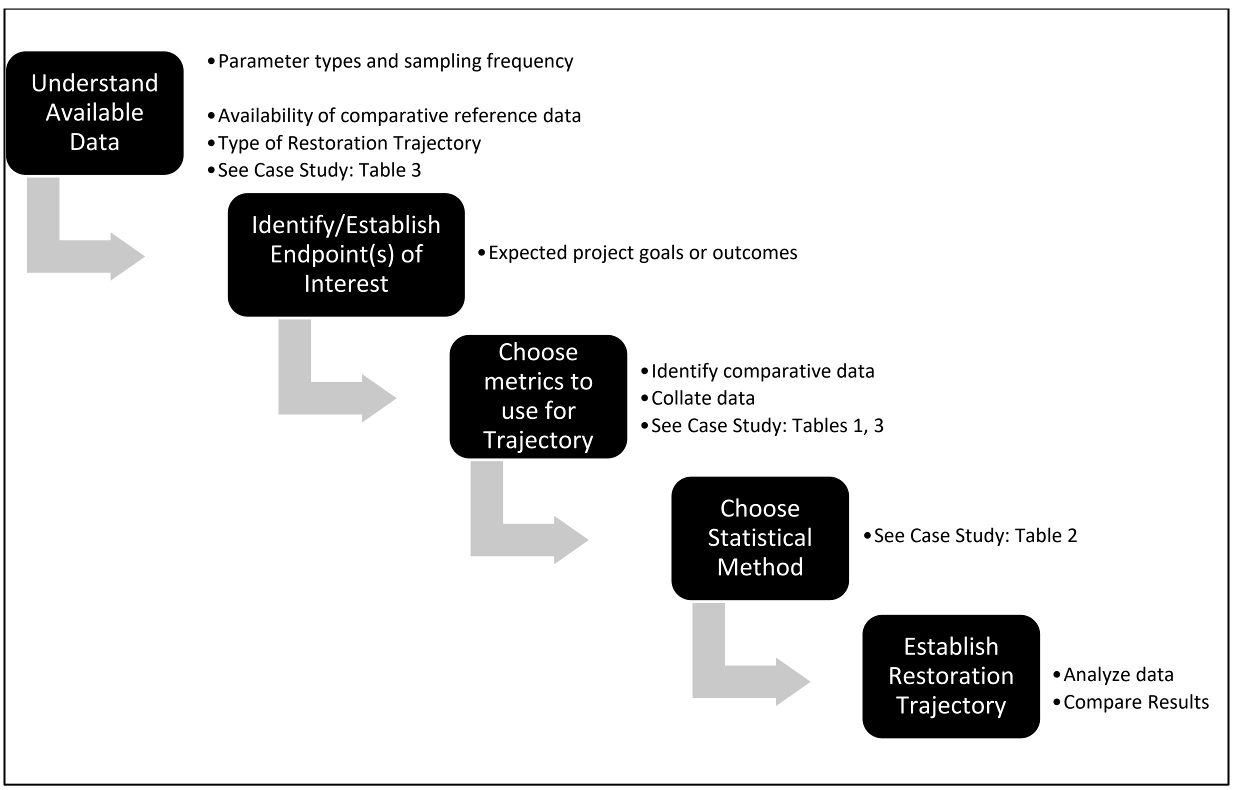
Reference	Location	Method	Method details	Trajectory statistics
Craft et al. 2003	NC	CTST	Used chrono-sequence to evaluate progression of vegetation, soil and microbial, and consumer attributes in created marshes (range 1 to 28 years), paired reference marshes.	Standard, ANOVA, regression
Wallace, Callaway, and Zedler 2005	San Diego, CA	CTST, RSST	Assessed the effects of tidal creek excavation on restoration success compared to reference marsh.	Standard, ANOVA, hydraulic geometry regression
Konisky et al. 2006	ME	CTST	Synthesized state of monitoring programs for 36 salt-marsh restoration projects focusing on functional indicators.	Standard, ANOVA, regression, trend analysis
Howe and Simenstad 2007	San Francisco Bay, CA	CTST	Used stable isotope analysis to identify differences in food-web source contributions to consumers occupying marshes at different stages of restoration.	Standard, ANOVA, NMDS, SIMPER, ANOSIM, isotopic mixing model
Langman et al. 2012	Balbol Embayment, Saudi Arabia	CTST, RSST	Selected effective metrics to assess restoration of salt-marsh oil-spill sites and compared between reference, disturbed, and restored.	Multimetric Index (MMI) analysis, ANOVA, regression
Sharma, Goff, Cebrian, et al 2016	Portersville Bay, AL	RSST	Assessed the effects of wave-attenuation units on shoreline stabilization and habitat quality in a restored salt marsh.	Standard, repeated measures ANOVA (RMANOVA), PERMANOVA, Mann-Whitney, Kruskal-Wallis
Lee 2018	Puget Sound, WA	CTST, RSST	Analyzed coastal biota response when armored shorelines are restored through armoring removal, beach grading, and planting native vegetation. Assessed their responses across (a) monitored shorelines, (b) coastal biota type, (c) shoreline elevations, and (d) trajectory in time.	Meta-analysis, effect size (Cohen's d), *t* tests
Rezek et al 2017	Corpus Christi Bay, TX	CTST	Examined the structural and functional characteristics of a recently constructed marsh in comparison to a natural reference marsh to evaluate the short-term ecological success of the restoration.	Standard, ANOVA, Bray-Curtis similarity index, NMDS, PERMANOVA, Kruskal-Wallis, regression, stable isotope mixing model
Baunmann et al. 2018	AL, FL, LA, MS, TX	CTST	Literature review compared response ration of periwinkle and amphipod density in various-aged salt-marsh restoration sites.	Response ratio, *t* tests
Weinstein, Hazin, and Litvin 2019	Delaware Bay, NJ	CTST, RSST	Meta-analysis assessed response of nekton to salt-marsh restoration over 17-year timespan and compared across sites to develop trajectory measure.	Meta-analysis, standard effect size (Hedges' d), confidence intervals

Reference	Location	Method	Method details	Trajectory statistics
Ebbets et al. 2019	FL, LA, TX	CTST, RSST	Literature review and meta-analysis evaluated vegetation and soil parameters in a range of site ages against reference sites.	Response ratio, chi square, metaregression, linear regression, quantile regression, restricted maximum likelihood analysis
Rydgren et al. 2019	Norway (not conducted in salt marsh)	CTST, RSST	Developed ordination regression-based approach for predicting time-to-boreal-forest recovery that allows both linear and asymptotic (logarithmic) relationships of compositional change with time. The approach uses distances between restored and reference plots along the successional gradient, represented by a vector in ordination space, to predict time to recovery.	Ordination regression-based approach
Wasson et al. 2019	CA, LA, MD, MS, NJ, RI	CTST	Scaled data from previous studies to analyze metrics of marsh vegetation, elevation, and hydrological metrics as trajectory measures against reference sites.	Multidimensional scaling analysis, linear regression, analysis of similarity, correlation, canonical analysis of principle coordinates

2.2 Case study: Trajectory development

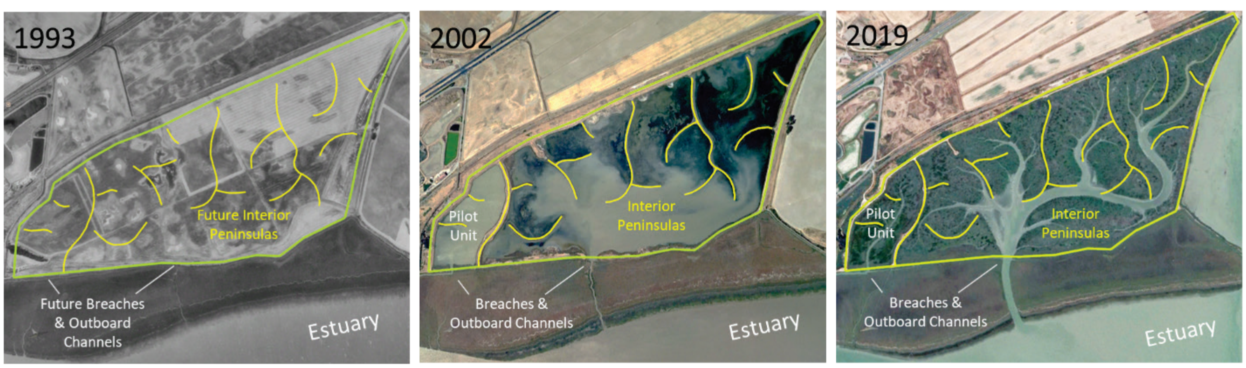
Here, we provide a practical example regarding the considerations and limitations one may encounter while planning to assess the trajectory of salt-marsh restorations using previously collected (archival) data. We then discuss the influence supplementary data collection can have on determining statistical approaches and the inferences drawn. Developing a restoration trajectory requires five components: (1) establishing a background in the available data or plans for data collection, (2) understanding the restoration goals (end points), (3) using the data and end points to identify appropriate metrics, (4) choosing a statistical method, and (5) performing the analysis (Figure 1). As an example of how to step through this process, we focus on data produced from long-term monitoring efforts (1996–2015) completed within a restored salt marsh in northern San Pablo Bay, California.

Figure 1. Conceptual diagram of restoration trajectory development process (plaintext version available in Appendix).



The Sonoma Baylands Wetland Demonstration Project (Sonoma Baylands) is a 303 ac (1.23 km^2)* restoration project carried out by USACE–San Francisco District and the California State Coastal Conservancy (CSCC) to restore tidal marsh habitat along the north margin of San Pablo Bay, Sonoma County, California (Figure 2). The project used dredged material to restore, protect, and expand the Baylands for the purpose of preserving waterfowl, fish, and other wetland-dependent species of plants and animals (USACE 1994). Initiated in 1994, construction efforts at Sonoma Baylands consisted of (1) creating a main perimeter levee, (2) multiple interior peninsulas to serve as wave breaks and to promote sediment accrual, (3) excavation of two outboard channels to allow for tidal exchange with estuarine waters, and (4) placement of nearly 2 million cubic yards of dredge material to raise surface elevations within optimal elevations for colonization by marsh vegetation. In 1996, following one to two years of dredge sediment consolidation, operators restored tidal inundation to the interior of the Sonoma Baylands by breeching the perimeter levee at the two outboard channel locations, consequently connecting the marsh plain with adjacent estuarine waters.

Figure 2. Aerial photographs of the Sonoma Baylands project area in 1993 prior to breaching the perimeter levee (*left*), 8 years postbreaching in 2002 (*middle*), and a recent image from 2019, 23 years postbreaching (*right*). The *green polygon* traces the location of the perimeter levee; *yellow lines* trace the centerlines of the interior peninsulas.



The project was constructed with the expectation that following site construction and re-establishment of tidal inundation, the evolution of the Sonoma Baylands should proceed as follows: (1) outboard channels reach

* For a full list of the unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 245–47, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

short-term equilibrium geometry within 3 to 5 years; (2) within 10 years, marsh-plain elevation should support establishment of cordgrass and pickleweed and vegetation will border mudflats as well as pannes; and (3) after ~30 years, the marsh plain will aggrade to ~+3.5 ft NGVD, or National Geodetic Vertical Datum—approximately MHHW, or mean higher high water—and vegetation will be mostly pickleweed and a fully developed slough channel system will have evolved (Entrix et al. 1991; USACE 1994; USACE and CSCC 1995). To track site evolution and evaluate the overall trajectory of the Sonoma Baylands restoration, managers established six physical and six biological performance criteria to guide monitoring efforts focused on both physical and biological parameters (USACE 1994). Monitoring of the site began in 1996 following restoration of tidal inundation and terminated in 2015 (Table 3). At this point, most of the physical and biological performance criteria were met, and remaining criteria were to be measured at later points (20–30 years from breaching). Although the monitoring program was in place, not all parameters were measured in a consistent manner through time.

Prior to beginning a trajectory analysis for restored salt marshes, such as the Sonoma Baylands, it is important to consider several key attributes of the site and available data, which will ultimately determine which type of trajectory analysis to use. First, it is important to understand the types of data available. For the Sonoma Baylands, the monitoring program focused on ~20 parameters (metrics) within three major categories: physical, floral, and faunal; however, investigators did not measure all parameters at the same frequency or intensity (Table 3). For example, investigators measured water quality only for the first 3 years (1996–1998) while performing annual elevation surveys for 19 years (1996–2014, marsh vegetation establishment, tidal regime). Next, it is important to consider whether there are comparative data available from nearby reference (that is, usually mature salt marsh) or control sites (that is, area not subject to restoration activities). If comparative data exists, determine whether the temporal range coincides with the range over which investigators collected restoration site data. In the case of the Sonoma Baylands, there is some limited complementary data from nearby mature salt marshes for certain parameters (for example, fish, birds, water quality, soil chemistry); however, these reference data only span a short time during the initial phase of restoration. Given this information, a trajectory analysis for the

Sonoma Baylands would likely take the form of an RSST and concentrate on parameters measured over the longest time span.

The next step would be to choose metrics (parameters) to use for the trajectory analysis. These metrics should provide insight into either the performance, function, or condition of the restored salt marsh. For this exercise, we choose to select metrics that represent measures of performance regarding the three main expectations for the evolution of the Sonoma Baylands following restoration of tidal influence (levee breaching). The first expectation is that outboard channels reach short-term equilibrium geometry within 3 to 5 years. Data from annual cross-section elevation surveys can be plotted as a function of time and compared to the predicted short-term equilibrium geometry. The annual cross-section data were collected every year for 13 years, and then every other year until 2014 (Table 3). Performing a linear regression would then determine the rate at which outboard channels are approaching the predicted equilibrium and whether this expectation has been met within 3 to 5 years postbreaching. The second expectation following levee breaching was that within 10 years, marsh-plain elevation should support establishment of cordgrass and pickleweed and that vegetation would border mudflats as well as pannes. Data from annual vegetation transects and aerial photography can be plotted through time to determine changes in marsh-plain vegetation cover and community structure (Table 3). However, to assess whether specific vegetation types are bordering mudflats and pannes, aerial photography (initiated in 2005, 9 years postbreach) would need to be digitally analyzed to classify and track the vegetation community occupying border areas through time. The final expectation of the evolution of Sonoma Baylands was that after ~30 years the marsh plain will aggrade to approximately +3.5 ft NGVD, that vegetation will be mostly pickleweed, and that a fully developed slough channel system will have evolved. Analyzing a restoration trajectory to address this expectation requires examination of a number of metrics through time as well as model prediction into the future, because available data only spans 20 years. Monitoring of the Sonoma Baylands included elevation transects across the marsh plain by surveying and by the installation of sediment elevation tables in 2005 (Table 3). A regression analysis of these elevation data through time would provide the necessary functional relationship to predict future elevation changes. To examine the trajectory of vegetation cover and channel morphology, survey data along internal transects could be compared to data generated by aerial photography conducted post-2005.

Table 3. Summary of data collected at the Sonoma Baylands restoration site through time. The letter *X* indicates data type collected. Row color corresponds to the type of attribute (that is, *orange* for physical parameters, *blue* for water quality, *green* for floral response, and *red* for faunal response).

	Report number	'96	'97	'98	'99	'00[a]	'01	'02	'03	'04[a]	'05	'06	'07	'08	'09	'10[b]	'11	'12	'13	'14	'15	'17
Attribute		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Physical parameters	Dredge material fill elevations (RS)	X	X	X	X	X	X	X	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Dredge material fill elevations (ET)	—	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	—	X	—	—	—
	Chemical constituents	—	X	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Exterior tidal channels (XS)	X	X	X	X	X	X	X	X	X	X	X	X	X	—	X	—	X	—	X	—	—
	Tide regime	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	—	—
	Peninsula crest elevation	X	—	X	X	X	X	—	—	—	X	—	—	—	—	—	—	—	—	—	—	—
	Perimeter levee settlement	X	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Tidal sedimentation (RS)	X	X	X	X	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Tidal sedimentation (ET)	—	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	—	X	—	—	—
	Tidal sedimentation (SET)	—	—	—	—	—	—	—	—	—	X	X	X	X	X	X	X	—	X	—	—	—
	Geotechnical investigation (cores)	—	—	—	—	—	—	—	—	—	—	—	X	—	—	—	—	—	—	—	—	—
	Control point surveys (BM)	—	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	—	—
	Internal channel development (ET/AP)	—	X	X	X	X	X	X	X	X[c]	X[c]	X[c]	X[c,d]	X[c]	X[c]	X[c]	X[c]	X[c]	X[c]	X[c]	—	—
—	Water quality	X	X	X	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Floral response	Marsh vegetation establishment	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	—	—
	Marsh vegetation cover (VT)	—	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	—	X	—	—	—
	Marsh vegetation cover (AP)	—	—	—	—	—	—	—	—	—	X[e]	X[e]	X[e]	X[e]	X[e]	X[e]	X[e]	X[e]	X[e]	X[e]	—	X
	Photodocumentation	—	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	—	—

Attribute	Report number	'96	'97	'98	'99	'00[a]	'01	'02	'03	'04[a]	'05	'06	'07	'08	'09	'10[b]	'11	'12	'13	'14	'15	'17
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
	Aerial photographs	X	—	—	X	—	—	X	X	X	X	X	X	X	X	X	X	X	X	X	—	X
Faunal response	Birds	—	X	X	X	X	X	X	X	X	X	X	X[a]	X	X	X	X	X	X	X	—	—
	Fishes	X	X	—	X	X	X	X	—	X	—	X	—	—	X	X	X	X	X	X	—	—
	Endangered species (CR call surveys)	X	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	X	X	X	—
	Endangered species (SMHM habitat)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	X	—	—	—	X
	Benthic macroinvertebrate colonization	—	X	X	X	X	X	X	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Note: RS—resistivity staffs; ET—elevation transects; VT—vegetation transects; AP—aerial photography; CR—clapper rail; SMHM—salt-marsh harvest mouse; BM—benchmark surveys; and XS—cross-section transect.

[a] Changes in monitoring plan design, RS abandoned

[b] 15-year report

[c] Channel morphology investigated using ET and AP

[d] Additional transects added (n = 4)

[e] Spectral analysis of colored infrared air photos (CIR Aps)

3 Conclusion

At a time when multiple stressors threaten coastal salt marshes—from development to diversions to climate change—marsh restoration using dredged material provides a means of re-establishing resilient coastal ecosystems. Measuring the success of these projects, however, can be difficult. Most natural existing marshes developed over hundreds or thousands of years and represent an end point that may not be seen within a period of monitoring. In addition, if all reference areas are degraded due to relative sea level rise or other chronic stressors, they may not currently represent the goals of restoration: a self-sustaining marsh.

Building restoration trajectories based either on the long-term monitoring records available or from the composite of multiples sites of different ages shows how different metrics progress over time and helps determine reasonable success criteria for new restorations.

Bibliography

Armitage, Anna R., Chuan-Kai Ho, Eric N. Madrid, Michael T. Bell, and Antoinetta Quigg. 2014. "The Influence of Habitat Construction Technique on the Ecological Characteristics of a Restored Brackish Marsh." *Ecological Engineering* 62 (January): 33–42. https://doi.org/10.1016/j.ecoleng.2013.10.021.

Barth, Hans-Jörg. 2003. "The Influence of Cyanobacteria on Oil Polluted Intertidal Soils at the Saudi Arabian Gulf Shores." *Marine Pollution Bulletin* 46, no. 10 (October): 1245–52. https://doi.org/10.1016/S0025-326X(03)00374-6.

Baumann, Matthew S., Gail F. Fricano, Katie Fedeli, Claire E. Schlemme, Mary C. Christman, and Melissa Vernon Carle. 2018. "Recovery of Salt Marsh Invertebrates Following Habitat Restoration: Implications for Marsh Restoration in the Northern Gulf of Mexico." *Estuaries and Coasts* 43 (November 2020): 1711–21. https://doi.org/10.1007/s12237-018-0469-5.

Blancher II, Eldon C., Richard A. Park, Jonathan S. Clough, Scott P. Milroy, W. Monty Graham, Chet F. Rakocinski, J. Read Hendon, Jerry D. Wiggert, and Robert Leaf. 2017. "Establishing Nearshore Marine Secondary Productivity Baseline Estimates for Multiple Habitats in Coastal Mississippi and Alabama Using AQUATOX 3.1 NME for Use in the Deepwater Horizon Natural Resource Damage Assessment." *Ecological Modelling* 359 (September): 49–68. https://doi.org/10.1016/j.ecolmodel.2017.05.004.

Boyer, Katharyn E., John C. Callaway, and Joy B. Zedler. 2000. "Evaluating the Progress of Restored Cordgrass (*Spartina foliosa*) Marshes: Belowground Biomass and Tissue Nitrogen." *Estuaries* 23, no. 5 (October): 711–21. https://doi.org/10.2307/1352897.

CPRAL (Coastal Protection and Restoration Authority of Louisiana). 2017. *Louisiana's Comprehensive Master Plan for a Sustainable Coast*. Baton Rouge: Coastal Protection and Restoration Authority of Louisiana. https://coastal.la.gov/wp-content/uploads/2017/04/2017-Coastal-Master-Plan_Web-Book_CFinal-with-Effective-Date-06092017.pdf.

Craft, Christopher. 2000. "Co-Development of Wetland Soils and Benthic Invertebrate Communities Following Salt Marsh Creation." *Wetlands Ecology and Management* 8, no. 2-3 (January): 197–207. https://doi.org/10.1023/A:1008448620605.

Craft, Christopher, Judy Reader, John N. Sacco, and Stephen W. Broome. 1999. "Twenty-Five Years of Ecosystem Development of Constructed *Spartina alterniflora* (Loisel) Marshes." *Ecological Applications* 9, no. 4 (November): 1405–19. https://doi.org/10.1890/1051-0761(1999)009[1405:TFYOED]2.0.CO;2.

Craft, Christopher, Patrick Megonigal, Stephen Broome, Jan Stevenson, Robert Freese, Jeff Cornell, Lei Zheng, and John Sacco. 2003. "The Pace of Ecosystem Development of Constructed *Spartina alterniflora* Marshes." *Ecological Applications* 13, no. 5 (October): 1417–32. https://doi.org/10.1890/02-5086.

Craft, Christopher, Stephen Broome, and Carlton Campbell. 2002. "Fifteen Years of Vegetation and Soil Development After Brackish-Water Marsh Creation." *Restoration Ecology* 10, no. 2 (June): 248–58. https://doi.org/10.1046/j.1526-100X.2002.01020.x.

Dahl, Thomas E., and Susan-Marie Stedman. 2013. *Status and Trends of Wetlands in the Coastal Watersheds of the Conterminous United States 2004 to 2009*. Washington, DC: US Department of the Interior–Fish and Wildlife Service and National Oceanic and Atmospheric Administration–National Marine Fisheries Service. https://www.fws.gov/sites/default/files/documents/Status-and-Trends-of-Wetlands-In-the-Coastal-Watersheds-of-the-Conterminous-US-2004-to-2009.pdf.

Delaney, Tim P., James W. Webb, and Thomas J. Minello. 2000. "Comparison of Physical Characteristics between Created and Natural Estuarine Marshes in Galveston Bay, Texas." *Wetlands Ecology and Management* 8, no. 5 (October): 343–52. https://doi.org/10.1023/A:1008439420830.

Dobson, Andrew P., Anthony David Bradshaw, and Alan J. M. Baker. 1997. "Hopes for the Future: Restoration Ecology and Conservation Biology." *Science* 277, no. 5325 (July): 515–22. https://doi.org/10.1126/science.277.5325.515.

Ebbets, Allison L., Diana R. Lane, Philip Dixon, Terill A. Hollweg, Mary T. Huisenga, and Jessica Gurevitch. 2019. "Using Meta-analysis to Develop Evidence-Based Recovery Trajectories of Vegetation and Soils in Restored Wetlands in the Northern Gulf of Mexico." *Estuaries and Coasts* 43 (November 2020): 1692–710. https://doi.org/10.1007/s12237-019-00536-y.

Entrix, Sonoma Land Trust, Philip Williams and Associates, Gahagan and Brian Associates, and CSCC (California State Coastal Conservancy). 1991. *Sonoma Baylands Enhancement Project: Technical Studies*. Walnut Creek, CA: Entrix.

Fraser, Lauchlan H., William L. Harrower, Heath W. Garris, Scott Davidson, Paul D. N. Hebert, Rick Howie, Anne Moody, et al. 2015. "A Call for Applying Trophic Structure in Ecological Restoration." *Restoration Ecology* 23, no. 5 (September): 503–7. https://doi.org/10.1111/rec.12225.

Gabler Christopher A., Michael J. Osland, James B. Grace, Camille L. Stagg, Richard H. Day, Stephen B. Hartley, Nicholas M. Enwright, Andrew S. From, Meagan L. McCoy, and Jennie L. McLeod. 2018. "Macroclimatic Change Expected to Transform Coastal Wetland Ecosystems This Century." *Nature Climate Change* 7 (January): 142–47. https://doi.org/10.1038/nclimate3203.

Garvey, K. J., and S. Brodeur. 2016. "Huntington Harbour Dredging Project: Case Study of Dredge Material Re-Use with Multiple Benefits." In *Ports 2016: Port Planning and Development*, 14th Triennial International Conference, 12–15 June, New Orleans, LA, edited by Don Oates, Elizabeth Burkhart, and Jennifer Grob, 679–88. https://doi.org/10.1061/9780784479919.070.

Gratton, Claudio, and Robert F. Denno. 2006. "Arthropod Food Web Restoration Following Removal of an Invasive Wetland Plant." *Ecological Applications* 16, no. 2 (April): 622–31. https://doi.org/10.1890/1051-0761(2006)016[0622:AFWRFR]2.0.CO;2.

Havens, Kirk J., Lyle M. Varnell, and Julie G. Bradshaw. 1995. "An Assessment of Ecological Conditions in a Constructed Tidal Marsh and Two Natural Reference Tidal Marshes in Coastal Virginia." *Ecological Engineering* 4, no. 2 (February): 117–41. https://doi.org/10.1016/0925-8574(94)00051-6.

Heberger, Matthew, Heather Cooley, Pablo Herrera, Peter H. Gleick, and Eli Moore. 2009. *The Impacts of Sea-Level Rise on the California Coast*. CEC-500-2009-024-F. Sacramento: California Climate Change Center. https://tamug-ir.tdl.org/bitstream/handle/1969.3/29130/sea-level-rise.pdf?sequence=1.

Hobbs, Richard J., and Harold A. Mooney. 1993. "Restoration Ecology and Invasions." In *Nature Conservation 3: Reconstruction of Fragmented Ecosystems*, edited by Paul R. Ehrlich, 127–33. Chipping Norton, UK: Surrey Beatty. https://hdl.handle.net/102.100.100/243147?index=1.

Howe, Emily R., and Charles A. Simenstad. 2007. "Restoration Trajectories and Food Web Linkages in San Francisco Bay's Estuarine Marshes: A Manipulative Translocation Experiment." *Marine Ecology Progress Series* 351 (December): 65–76. https://doi.org/10.3354/meps07120.

Hudson, Peter J., Andrew P. Dobson, and Kevin D. Lafferty. 2006. "Is a Healthy Ecosystem One That Is Rich in Parasites?" *Trends in Ecology and Evolution* 21, no. 7 (July): 381–85. https://doi.org/10.1016/j.tree.2006.04.007.

Hughes, Francine M. R., Adrian Colston, and J. Owen Mountford. 2005. "Restoring Riparian Ecosystems: The Challenge of Accommodating Variability and Designing Restoration Trajectories." *Ecology and Society* 10, no. 1 (June): 12. https://www.ecologyandsociety.org/vol10/iss1/art12/.

Huspeni, Todd C., and Kevin D. Lafferty. 2004. "Using Larval Trematodes that Parasitize Snails to Evaluate a Saltmarsh Restoration Project." *Ecological Applications* 14, no. 3 (June): 795–804. https://doi.org/10.1890/01-5346.

Karr, James R. 1981. "Assessment of Biotic Integrity Using Fish Communities." *Fisheries* 6, no. 6 (November): 21–27. https://doi.org/10.1577/1548-8446(1981)006%3C0021:AOBIUF%3E2.0.CO;2.

Kentula, Mary E. 2000. “Perspectives on Setting Success Criteria for Wetland Restoration.” *Ecological Engineering* 15, nos. 3–4 (July): 199–209. https://doi.org/10.1016/S0925-8574(00)00076-8.

Kirwan, Matthew L., and J. Patrick Megonigal. 2013. “Tidal Wetland Stability in the Face of Human Impacts and Sea-Level Rise.” *Nature* 504, no. 7478 (December): 53–60. https://doi.org/10.1038/nature12856.

Kollmann, Johannes, Sebastian T. Meyer, Rolf Bateman, Timo Conradi, Martin M. Gossner, Milton de Souza Mendonça Jr., Geraldo W. Fernandes, et al. 2016. “Integrating Ecosystem Functions into Restoration Ecology—Recent Advances and Future Directions.” *Restoration Ecology* 24, no. 6 (September): 722–30. https://doi.org/10.1111/rec.12422.

Konisky, Raymond A., David M. Burdick, Michele Dionne, and Hilary A. Neckles. 2006. “A Regional Assessment of Salt Marsh Restoration and Monitoring in the Gulf of Maine.” *Restoration Ecology* 14, no. 4 (December): 516–25. https://doi.org/10.1111/j.1526-100X.2006.00163.x.

Langman, Owen C., Jason A. Hale, Chris D. Cormack, Michael J. Risk, and Sharook P. Madon. 2012. “Developing Multimetric Indices for Monitoring Ecological Restoration Progress in Salt Marshes.” *Marine Pollution Bulletin* 64, no. 4 (April): 820–35. https://doi.org/10.1016/j.marpolbul.2012.01.030.

Larkin, Daniel J., Sharook P. Madon, Janelle M. West, and Joy B. Zedler. 2008. “Topographic Heterogeneity Influences Fish Use of an Experimentally Restored Tidal Marsh.” *Ecological Applications* 18, no. 2 (March): 483–96. https://doi.org/10.1890/06-1984.1.

Lee, Timothy S., Jason D. Toft, Jeffrey R. Cordell, Megan N. Dethier, Jeffrey W. Adams, and Ryan P. Kelly. 2018. “Quantifying the Effectiveness of Shoreline Armoring Removal on Coastal Biota of Puget Sound.” *PeerJ* 6 (February): e4275. https://doi.org/10.7717/peerj.4275.

Lewis, Roy R., III. 2000. “Ecologically Based Goal Setting in Mangrove Forest and Tidal Marsh Restoration.” *Ecological Engineering* 15, nos. 3–4 (July): 191–98. https://doi.org/10.1016/S0925-8574(00)00070-7.

Magnuson, John J., Henry A. Regier, W. John Christie, and William C. Sonzogni. 1980. “To Rehabilitate and Restore Great Lakes Ecosystems.” In *The Recovery Process in Damaged Ecosystems*, edited by John Cairns Jr, 95–112. Ann Arbor, MI: Ann Arbor Science.

Minello, Thomas J., and James W. Webb Jr. 1997. “Use of Natural and Created *Spartina alterniflora* Salt Marshes by Fishery Species and Other Aquatic Fauna in Galveston Bay, Texas, USA.” *Marine Ecology Progress Series* 151 (May): 165–79. https://doi.org/10.3354/meps151165.

Minello, Thomas J., Roger J. Zimmerman, and Richard Medina. 1994. “The Importance of Edge for Natant Macrofauna in a Created Salt Marsh.” *Wetlands* 14, no. 3 (September): 184–98. https://doi.org/10.1007/BF03160655.

Morgan, Pamela A., and Frederick T. Short. 2002. “Using Functional Trajectories to Track Constructed Salt Marsh Development in the Great Bay Estuary, Maine/New Hampshire, USA.” *Restoration Ecology* 10, no. 3 (September): 461–73. https://doi.org/10.1046/j.1526-100X.2002.01037.x.

Neckles, Hilary A., Michele Dionne, David M. Burdick, Charles T. Roman, Robert Buchsbaum, and Eric Hutchins. 2002. “A Monitoring Protocol to Assess Tidal Restoration of Salt Marshes on Local and Regional Scales.” *Restoration Ecology* 10, no. 3 (September): 556–63. https://doi.org/10.1046/j.1526-100X.2002.02033.x.

Nyman, J.A., and R.D. DeLaune. 1999. “Four Potential Impacts of Global Sea Level Rise on Coastal Marsh Stability.” *Current Topics in Wetland Biogeochemistry* 3:112–17. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1072.642&rep=rep1&type=pdf.

O’Connell, Jessica L., Merryl Alber, and Steven C. Pennings. 2020. “Microspatial Differences in Soil Temperature Cause Phenology Change on Par with Long-Term Climate Warming in Salt Marshes.” *Ecosystems* 23, no. 3 (July): 498–510. https://doi.org/10.1007/s10021-019-00418-1.

Odum, William E., Eugene P. Odum, and Howard T. Odum. 1995. “Nature’s Pulsing Paradigm.” *Estuaries* 18, no. 4 (December): 547–55. https://doi.org/10.2307/1352375.

Palmer, Margaret A., Joy B. Zedler, and Donald A. Falk, eds. 2016. *Foundations Of Restoration Ecology*. Washington, DC: Island Press. https://doi.org/10.5822/978-1-61091-698-1.

Pendleton, Linwood, Daniel C. Donato, Brian C. Murray, Stephen Crooks, W. Aaron Jenkins, Samantha Sifleet, Christopher Craft, et al. 2012. “Estimating Global ‘Blue Carbon’ Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems.” *PLOS ONE* 7, no. 9 (September): e43542. https://doi.org/10.1371/journal.pone.0043542.

Peterson, Charles H., and Romuald N. Lipcius. 2003. “Conceptual Progress Towards Predicting Quantitative Ecosystem Benefits of Ecological Restorations.” *Marine Ecology Progress Series* 264 (December): 297–307. https://doi.org/10.3354/meps264297.

Posey, Martin H., Troy D. Alphin, and Christopher M. Powell. 1997. “Plant and Infaunal Communities Associated with a Created Marsh.” *Estuaries* 20, no. 1 (March): 42–47. https://doi.org/10.2307/1352718.

Reed, Denise J. 2002. "Sea-Level Rise and Coastal Marsh Sustainability: Geological and Ecological Factors in the Mississippi Delta Plain. *Geomorphology* 48, nos. 1–3 (November): 233–43. https://doi.org/10.1016/S0169-555X(02)00183-6.

Rezek, Ryan J., Benoit Lebreton, Blair Sterba-Boatwright, and Jennifer Beseres Pollack. 2017. "Ecological Structure and Function in a Restored Versus Natural Salt Marsh." *PlOS ONE* 12, no. 12 (December): e0189871. https://doi.org/10.1371/journal.pone.0189871.

Roman, Charles T. 2017. "Salt Marsh Sustainability: Challenges During an Uncertain Future." *Estuaries and Coasts* 40, no. 3 (August): 711–16. https://doi.org/10.1007/s12237-016-0149-2.

Roman, Charles T., Kenneth B. Raposa, Susan C. Adamowicz, Mary-Jane James-Pirri, and John G. Catena. 2002. "Quantifying Vegetation and Nekton Response to Tidal Restoration of a New England Salt Marsh." *Restoration Ecology* 10, no. 3 (September): 450–60. https://doi.org/10.1046/j.1526-100X.2002.01036.x.

Rozas, Lawrence P., Philip Caldwell, and Thomas J. Minello. 2005. "The Fishery Value of Salt Marsh Restoration Projects." Special issue, *Journal of Coastal Research, Coastal Restoration: Where Have We Been, Where Are We Now, and Where Should We Be Going?* SI, no. 40 (Winter): 37–50. https://www.jstor.org/stable/25736614.

Rydgren, Knut, Rune Halvorsen, Joachim P. Töpper, Inger Auestad, Liv Norunn Hamre, Eelke Jongejans, and Jan Sulavik. 2019. "Advancing Restoration Ecology: A New Approach to Predict Time to Recovery." *Journal of Applied Ecology* 56, no. 1 (January): 225–34. https://doi.org/10.1111/1365-2664.13254.

Schreffler, David K., Charles A. Simenstad, and Ronald M. Thom. 1992. "Foraging by Juvenile Salmon in a Restored Estuarine Wetland." *Estuaries* 15, no. 2 (June): 204–13. https://doi.org/10.2307/1352693.

Sharma, Shailesh, Joshua Goff, Just Cebrian, and Carl Ferraro. 2016. "A Hybrid Shoreline Stabilization Technique: Impact of Modified Intertidal Reefs on Marsh Expansion and Nekton Habitat in the Northern Gulf of Mexico." *Ecological Engineering* 90 (May): 352–60. https://doi.org/10.1016/j.ecoleng.2016.02.003.

Sharma, Shailesh, Joshua Goff, Ryan M. Moody, Ashley McDonald, Dorothy Byron, Kenneth L. Heck Jr., Sean P. Powers, Carl Ferraro, and Just Cebrian. 2016. "Effects of Shoreline Dynamics on Saltmarsh Vegetation." *PLOS ONE* 11, no. 7 (July): e0159814. https://doi.org/10.1371/journal.pone.0159814.

Short, Frederick T., David M. Burdick, Catherine A. Short, Ryan C. Davis, and Pamela A. Morgan. 2000. "Developing Success Criteria for Restored Eelgrass, Salt Marsh and Mud Flat Habitats." *Ecological Engineering* 15, nos. 3–4 (July): 239–52. https://doi.org/10.1016/S0925-8574(00)00079-3.

Smith, R. Daniel, Alan Ammann, Candy Bartoldus, and Mark M. Brinson. 1995. *An Approach for Assessing Wetland Functions Using Hydrogeomorphic Classification, Reference Wetlands, and Functional Indices*. WES/TR/WRP-DE-9. Vicksburg, MS: US Army Corps of Engineers–Waterways Experiment Station. https://apps.dtic.mil/sti/pdfs/ADA307121.pdf.

Smith, Val H. 2003. "Eutrophication of Freshwater and Coastal Marine Ecosystems a Global Problem." *Environmental Science and Pollution Research* 10, no. 2 (March): 126–39. https://link.springer.com/article/10.1065/espr2002.12.142.

SER (Society for Ecological Restoration). 2004. *The SER International Primer on Ecological Restoration*. Version 2: October. Washington, DC: Society for Ecological Restoration. https://www.ser.org/resource/resmgr/custompages/publications/ser_publications/ser_primer.pdf.

Suding, Katharine N., and Richard J. Hobbs. 2009. "Threshold Models in Restoration and Conservation: A Developing Framework." *Trends in Ecology and Evolution* 24, no. 5 (May): 271–79. https://doi.org/10.1016/j.tree.2008.11.012.

Thorne, Karen M., Glen M. MacDonald, Rich F. Ambrose, Kevin J. Buffington, Chase M. Freeman, Christopher N. Janousek, Lauren N. Brown, et al. 2016. *Effects of Climate Change on Tidal Marshes along a Latitudinal Gradient in California*. US Geological Survey Open-File Report 2016-1125. Reston, VA: US Geological Survey. https://doi.org/10.3133/ofr20161125.

Thorne, Karen, Glen MacDonald, Glenn Guntenspergen, Richard Ambrose, Kevin Buffington, Bruce Dugger, Chase Freeman, et al. 2018. "US Pacific Coastal Wetland Resilience and Vulnerability to Sea-Level Rise." *Science Advances* 4, no. 2 (February): eaao3270. https://doi.org/10.1126/sciadv.aao3270.

Tong, Chunfu, Joseph J. Baustian, Sean A. Graham, and Irving A. Mendelssohn. 2013. "Salt-Marsh Restoration with Sediment-Slurry Application: Effects on Benthic Macroinvertebrates and Associated Soil–Plant Variables." *Ecological Engineering* 51 (February): 151–60. https://doi.org/10.1016/j.ecoleng.2012.12.010.

USACE (US Army Corps of Engineers) and CSCC (California State Coastal Conservancy). 1995. *Monitoring Plan, Sonoma Baylands Wetland Demonstration Project*.

USACE. 1994. *Sonoma Baylands Wetland Demonstration Project - Demonstration Project Report and Environmental Assessment*. Final Report. San Francisco, CA: USACE–San Francisco District.

VanZomeren, Christine M., Elizabeth O. Murray, and Damarys Acevedo-Mackey. 2019. *Marsh Assessment and Restoration Implementation at Three Salt Marshes in Response to Relative Sea Level Rise: A Report from Webinars and Supplemental Findings*. EMRRP Technical Notes Collection. ERDC/TN EMRRP-EBA-23 Vicksburg, MS: US Army Engineer Research and Development Center. https://hdl.handle.net/11681/32412.

Vincent, Robert E., David M. Burdick, and Michele Dionne. 2013. "Ditching and Ditch-Plugging in New England Salt Marshes: Effects on Hydrology, Elevation, and Soil Characteristics." *Estuaries and Coasts* 36, no. 3 (January): 610–25. https://doi.org/10.1007/s12237-012-9583-y.

Vincent, Robert E., David M. Burdick, and Michele Dionne. 2014. "Ditching and Ditch-Plugging in New England Salt Marshes: Effects on Plant Communities and Self-Maintenance." *Estuaries and Coasts* 37, no. 2 (July): 354–68. https://doi.org/10.1007/s12237-013-9671-7.

Wallace, Katy J., John C. Callaway, and Joy B. Zedler. 2005. "Evolution of Tidal Creek Networks in a High Sedimentation Environment: A 5-Year Experiment at Tijuana Estuary, California." *Estuaries* 28, no. 6 (December): 795–811. https://doi.org/10.1007/BF02696010.

Wasson, Kerstin, Neil K Ganju, Zafer Defne, Charlie Endris, Tracy Elsey-Quirk, Karen M Thorne, Chase M Freeman, Glenn Guntenspergen, David J Nowacki, and Kenneth B Raposa. 2019. "Understanding Tidal Marsh Trajectories: Evaluation of Multiple Indicators of Marsh Persistence." *Environmental Research Letters* 14, no. 12 (December): 124073. https://iopscience.iop.org/article/10.1088/1748-9326/ab5a94/meta.

Watson, E. B., K.B. Raposa, J.C. Carey, C. Wigand, and R.S. Warren. 2017. "Anthropocene Survival of Southern New England's Salt Marshes." *Estuaries and Coasts* 40 (May): 617–25. https://doi.org/10.1007/s12237-016-0166-1.

Watson, Elizabeth Burke, Cathleen Wigand, Earl W. Davey, Holly M. Andrews, Joseph Bishop, and Kenneth B. Raposa. 2017. "Wetland Loss Patterns and Inundation-Productivity Relationships Prognosticate Widespread Salt Marsh Loss for Southern New England." *Estuaries and Coasts* 40 (May): 662–81. https://doi.org/10.1007/s12237-016-0069-1.

Weinstein, Michael P., John H. Balletto, John M. Teal, and David F. Ludwig. 1996. "Success Criteria and Adaptive Management for a Large-Scale Wetland Restoration Project." Special issue, *Wetlands Ecology and Management*, *Hydrologic Restoration of Coastal Wetlands* 4, no. 2 (February): 111–27. https://doi.org/10.1007/BF01876232.

Weinstein, Michael P., John M. Teal, John H. Balletto, and Kenneth A. Strait. 2001. "Restoration Principles Emerging from One of the World's Largest Tidal Marsh Restoration Projects." *Wetlands Ecology and Management* 9, no. 5 (October): 387–407. https://doi.org/10.1023/A:1012058713910.

Weinstein, Michael P., Robert Hazen, and Steven Y. Litvin. 2019. "Response of Nekton to Tidal Salt-Marsh Restoration, a Meta-analysis of Restoration Trajectories." *Wetlands* 39, no. 3 (June): 575–85. https://doi.org/10.1007/s13157-018-1106-6.

Weinstein, Michael P., Steven Y. Litvin, and Vincent G. Guida. 2005. "Considerations of Habitat Linkages, Estuarine Landscapes, and the Trophic Spectrum in Wetland Restoration Design." Special issue, *Journal of Coastal Research*, *Coastal Restoration: Where Have We Been, Where Are We Now, and Where Should We Be Going?* SI, no. 40 (Winter): 51–63. https://www.jstor.org/stable/25736615.

Wingard, G. Lynn, and Jerome J. Lorenz. 2014. "Integrated Conceptual Ecological Model and Habitat Indices for the Southwest Florida Coastal Wetlands." *Ecological Indicators* 44 (September): 92–107. https://doi.org/10.1016/j.ecolind.2014.01.007.

Wozniak, Andrew S., Charles T. Roman, Sam C. Wainright, Richard A. McKinney, and Mary-Jane James-Pirri. 2006. "Monitoring Food Web Changes in Tide-Restored Salt Marshes: A Carbon Stable Isotope Approach." *Estuaries and Coasts* 29, no. 4 (August): 568–78. https://link.springer.com/article/10.1007/BF02784283.

Zedler, Joy B. and John C. Callaway. 1999. "Tracking Wetland Restoration: Do Mitigation Sites Follow Desired Trajectories?" *Restoration Ecology* 7, no. 1 (March): 69–73. https://doi.org/10.1046/j.1526-100X.1999.07108.x.

Zedler, Joy B., and John C. Callaway. 2000. "Evaluating the Progress of Engineered Tidal Wetlands." *Ecological Engineering* 15, nos. 3–4 (July): 211–25. https://doi.org/10.1016/S0925-8574(00)00077-X.

Zedler, Joy B., and Ren Langis. 1991. "Authenticity: Comparisons of Constructed and Natural Salt Marshes of San Diego Bay." *Restoration and Management Notes* [*Ecological Restoration*] 9, no. 1 (Summer): 21–25. http://er.uwpress.org/content/9/1/21.full.pdf.

Zhao, Qingqing, Junhong Bai, Laibin Huang, Binhe Gu, Qiongqiong Lu, and Zhaoqin Gao. 2016. "A Review of Methodologies and Success Indicators for Coastal Wetland Restoration." *Ecological Indicators* 60 (January): 442–52. https://doi.org/10.1016/j.ecolind.2015.07.003.

Appendix: Figure 1 Diagram in Plaintext

This appendix provides a plaintext version of Figure 1.

- Step 1: Understand Available Data
  - Parameter types and sampling frequency
  - Availability of comparative reference data
  - Type of Restoration Trajectory
  - See Case Study: Table 3
- Step 2: Identify/Establish Endpoint(s) of Interest
  - Expected project goals or outcomes.
- Step 3: Choose metrics to use for Trajectory
  - Identify comparative data
  - Collate data
  - See Case Study: Tables 1, 3
- Step 4: Choose Statistical Method
  - See Case Study: Table 2
- Step 5: Establish Restoration Trajectory
  - Analyze data
  - Compare Results

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14. ABSTRACT

This special report identifies metrics (standard and novel) and analytic approaches to developing trajectories and then describes the conceptual process of using those metrics and approaches to develop restoration trajectories to inform adaptive management in salt-marsh systems. We identify the composite time series trajectory (CTST) approach, in which metrics are measured from restoration sites of different ages within a small spatial range, and the retrospective single-site trajectory (RSST) approach, in which the same restoration metrics are measured over time at one restoration site. In all, we assessed the metrics of 39 studies of salt-marsh restoration in the United States between 1991 and 2019.

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