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Success criteria and adaptive management for a large-scale wetland restoration project

Michael P. Weinstein[1], John H. Balletto[2], John M. Teal[3] and David F. Ludwig[4]
[1]TEVA Environmental Associates, Inc., 854 Ridgewood Road, Millburn, NJ, USA; [2]Public Service Electric and Gas Company, Estuary Enhancement Program, Hancocks Bridge, NJ 08038, USA; [3]Woods Hole Oceanographic Institution, Red Field 212, Water Street, Woods Hole, MA 02543, USA; [4]EA Engineering, Science and Technology, 11019 McCormick Road, Hunt Valley, MD 21031, USA

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Abstract

We are using a 20+ year photographic history of relatively undisturbed and formerly diked sites to predict the restoration trajectories and equilibrium size of a 4,050 ha salt marsh on Delaware Bay, New Jersey (USA). The project was initiated to offset the loss of finfishes from once-through cooling at a local power plant. We used a simple food chain model to estimate the required restoration size. This model assumed that annual macrophyte detritus production and benthic algal production resulted in production of finfishes, including certain species of local interest. Because the marsh surface and intertidal drainage system are used by many finfishes and are the focal points for exchange of detrital materials, the restoration planning focused on both vegetational and hydrogeomorphological parameters. Recolonization by *Spartina* spp. and other desirable taxa will be promoted by returning a natural hydroperiod and drainage configuration to two types of degraded salt marsh: diked salt hay (*Spartina patens*) farms and brackish marsh dominated by *Phragmites australis*. The criteria for success of the project address two questions: What is the "bound of expectation" for restoration success, and how long will it take to get there? Measurements to be made are macrophyte production, vegetation composition, benthic algal production, and drainage features including stream order, drainage density, channel length, bifurcation ratios and sinuosity. A method for combining these individual parameters into a single success index is also presented. Finally, we developed adaptive management thresholds and corrective measures to guide the restoration process.

Introduction

The restoration of 4,050 hectares of degraded salt marshes within the Delaware Bay is required by a permit issued to operate the Salem Generating Station (Fig. 1). The restoration area was determined from the relationship between net aboveground primary production and secondary production of four species of finfishes affected by the station, assuming that marsh macrophytes and algae contributed to the detrital food web of the estuary and support finfish production (Teal 1962, Haines 1979, Odum 1980, Nixon 1980, Deegan 1993). The food-chain model used neglected underground plant biomass and did not assess the habitat value of the restored marshes for fishes and invertebrates. Further, the area calculated to produce an equivalent biomass of finfish reduced because of the power plant operations was increased by a factor of about four to provide a margin of safety for the estimates.

Two kinds of degraded wetlands will be restored as part of this project. One is diked salt hay (*Spartina patens*) farms and the other is brackish, non-impounded salt marshes dominated by *Phragmites australis* (Fig. 1). The nearly 1780 hectares of salt hay farms are surrounded by perimeter dikes at approximately 1.5 m North American

Fig. 1. Location of the Salem Generating Station, marsh restoration areas, and marsh reference sites.

Vertical Datum (NAVD). Within the salt hay farms, the marsh plain has subsided or failed to accrete over the years so that artificially maintained high marsh vegetation is present. Much of the original marsh plain now ranges from about mean tide level to mean high water. At one location, the dikes were breached by storms in the fall of 1992. Tides have since inundated the site and most higher plants are either absent or dead. We expect similar mortality when the other diked farms are opened to the tides. This will result in a lag period before a site is recolonized by low marsh species.

The salt hay farms have been in continuous agriculture since the early 1950s but include some parcels diked as early as the 1700s. Most of the 2145 hectares of *P. australis* degraded wetlands to be restored were diked early in this century. These dikes were previously breached at unknown times.

The broad outline of the approach is to reintroduce tidal inundation at diked wetlands, and to enhance drainage by re-excavating higher order channels that filled in during the diked period. A program of herbicide spraying and controlled burning along with selected hydromodifications will be used to reduce undesirable dominance of *Phragmites australis* in non-impounded wetlands. This will enhance the exchange of detrital materials with the estuary and permit unrestricted marsh access by marine and estuarine fishes. This paper describes the intent, rationale and criteria used in this restoration program to measure success and make management changes due to unforeseen results.

Measures of restoration success

To judge whether the restoration effort will be successful, performance criteria (Kentula *et al.* 1993) were developed that serve to predict marsh function *in situ*, or the coupling of marsh-estuarine processes. The criteria are also embedded in an adaptive management framework (National Research Council 1992) designed to guide the general restoration process.

Initially, three categories of performance criteria were presented to regulatory agencies and became conditions of the project permit: (1) percent coverage of the marsh by vegetation, (2) reduction in *Phragmites australis* coverage, and, (3) percent open water. We expanded these criteria to include others specific to the project's central objective, which is to enhance finfish production in the Delaware Bay. A method for combining the criteria into a single index is also proposed.

A monitoring program initiated in 1995 will provide data for estimating the values for these additional criteria and will refine the measures of project success. Although these are not permitted conditions of the project they form the technical (not regulatory) basis for judging project success.

A framework for addressing restoration success

On the New Jersey side of Delaware Bay there are a number of "self-restored" salt marshes. Some that were diked for farming between the 1700s to the 1950s, have been restored by storms breaching the dikes. Others were restored after small openings were excavated in the dikes. In none of these restoration projects was there any active development of tidal channels in the marsh. In our project, we used the historical record to develop criteria to judge the progress and ultimate success of the restorations in which tidal channels will be re-established to speed up the restoration process.

From a practical standpoint, two questions must be addressed to judge restoration success: (1) how long will it take to restore the marshes, *i.e.*, what are the restoration trajectories? and, (2) what are the bounds that define the ultimate goal of the restorations? Kentula *et al.* (1993) noted that success should be defined in terms of the project objectives, *i.e.*, what is acceptable for a particular project in a specific locale. In our case, the objective is to enhance fisheries production in the Delaware Bay by restoring degraded marshes with as many aspects as possible of a natural system. The bounds we refer to are defined in terms of structural and functional characteristics of salt marshes that promote the production of finfishes, particularly the young of marine species using marshes during their early life history.

It would be a hopeless task to attempt to address all wetland functions comprehensively as part of this restoration program and most others. We cannot consider all of the functions associated with biogeochemical cycling and storage, hydrology, biological productivity, decomposition, community and wildlife habitat, etc. (Zedler 1992, Richardson, 1994). However, certain principles act as "unifying themes" that can be used to establish the specific restoration goals. There are features within all marsh landscapes that act as corridors to focus the movement of materials and energy among other elements of the system (Turner 1989). The marsh can be viewed as a network landscape (Forman and Godron 1986, Forman 1990) composed of two major elements: the vegetated intertidal marsh and open water. Hydrology appears to be a key forcing function (Mitsch and Gosselink 1993, Richardson 1994) that will reconfigure the drainage pattern of the restored sites and promote the growth of smooth cordgrass (*Spartina alterniflora*) and other plant taxa. Drainage density, sinuosity and other geomorphological characteristics of the restored marsh are also critical for maximizing wetland edge, and optimizing the exchange pathway between the marsh surface and the estu-

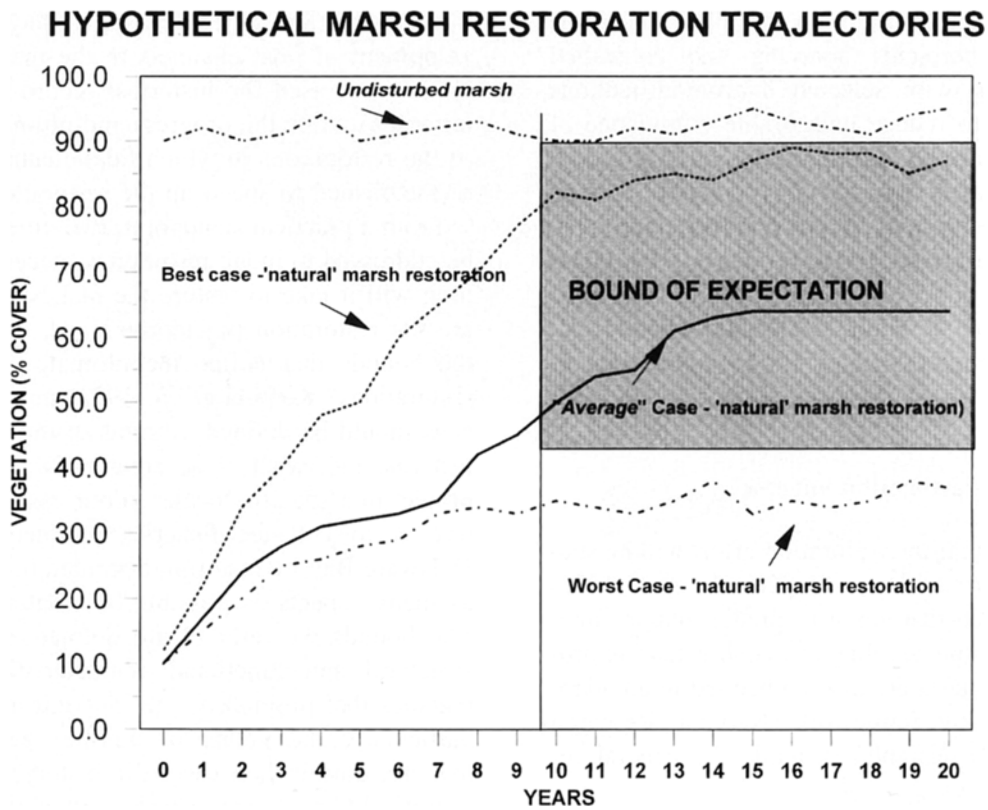

Fig. 2. Hypothetical curves for marsh restoration trajectories and restoration end-points. An asymptote is expected to be reached in about twelve to fifteen years. "Natural" marshes are restored systems that were previously diked and have returned to a natural state with little or no human intervention.

ary. Finally, reduction of *Phragmites australis* coverage and its replacement by other more desirable vegetation that degrades rapidly to detritus is a desired end-point of the restoration.

Thus, restoring functional salt marshes that promotes quality fish habitat and secondary production requires re-establishing desirable vegetation on the marsh plain, restoring a natural hydroperiod, and reproducing to the extent possible the entire mosaic of interactive structural elements of marsh habitat: tidal creeks, flats, vegetated areas, and ponds/pannes. We have determined the "bound of expectation" and restoration trajectories from the naturally restored and undisturbed marshes in the region, the "reference marshes". When the trajectories for a given restoration site fall within the bound, that site will be considered to be functionally equivalent to the reference marshes.

The role of vegetation in the salt marsh is well-known. Vegetation stabilizes the marsh surface, forms the basis of the detrital food web, and contributes detritus to the open waters of the estuary. The marsh surface and intertidal drainage system represented by tidal creeks and other open waters are utilized by many finfish and shellfish (McIvor and Odum 1988, Rozas *et al.* 1988). They are the focal point for fish foraging, and for exchange of detrital material and suspended sediments. Fish display much greater use of high density versus low density drainage habitats (Kneib 1994). The natural function of the salt marsh is thus tied not only to primary production on the marsh plain, but also to a well-developed dendritic pattern of tidal creeks. Wiegert and Pomeroy (1981) summarized this critical relationship by commenting that: "Our present view of the food web of the marsh and estuary suggests that the preservation of fisheries depends as much upon the protection of the smaller tidal creeks as upon protection of the marsh and its *Spartina* production."

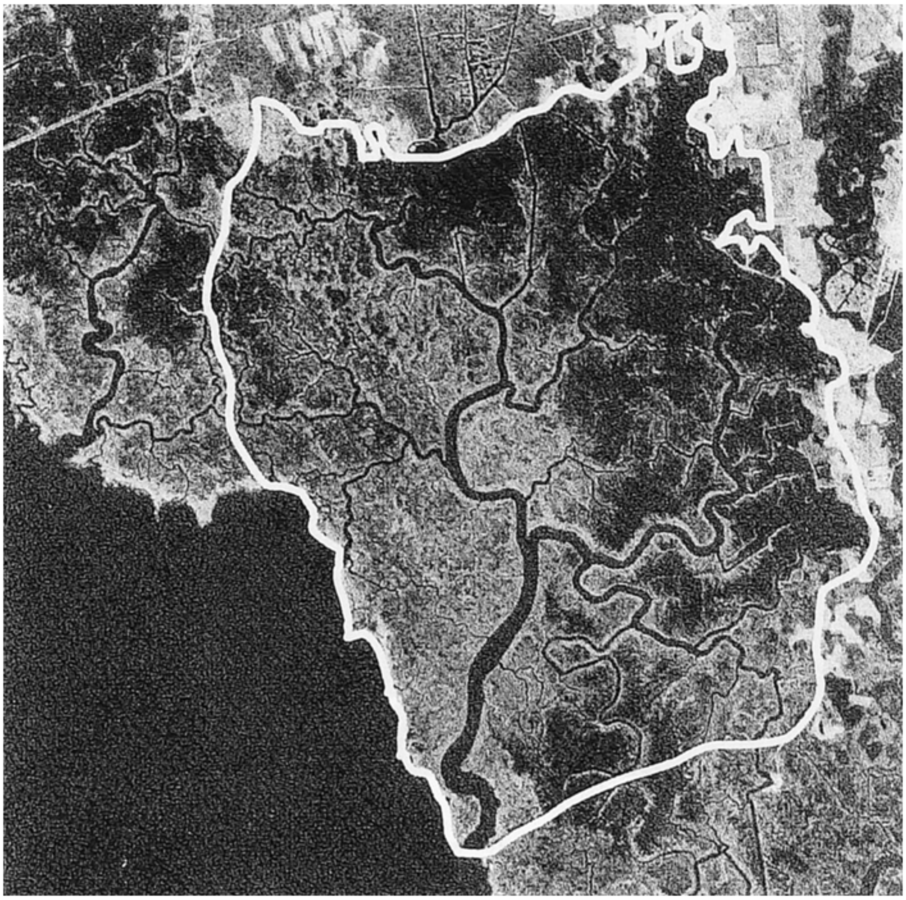

Fig. 3. Mad Horse Creek marsh, a relatively undisturbed 1709 ha reference site located in the meso-oligohaline portion of the estuary.

The process

The ecological criteria used are related to the production of macrophytes and are designed to address hydroperiod and hydrology characteristics of natural marshes by (1) restoring a flooding-draining cycle (hydroperiod) that promotes recolonization by *Spartina* spp. and other desirable taxa, and, (2) providing high quality fish habitat as intertidal drainage channels and flats connected to subtidal channels and other open water. As an example, the range of time-trajectories and the bound of expectation for revegetation rates are depicted by hypothetical curves in Fig. 2. Revegetation rates can be determined from published values (Bongiorno *et al.* 1974, Slavin and Shisler 1983, Roman *et al.* 1984, Bertness and Ellison 1987, Sinicrope *et al.* 1990), and by evaluating the natural restorations of formerly diked areas in Delaware Bay. However, few data are available and none at the scale of 1000s of ha restored. The most meaningful values will thus be ultimately derived from the project itself.

It is likely that the upper limit of the anticipated bound for most parameters will be represented by a relatively undisturbed reference marsh. The structural similarity between the undisturbed marshes and the natural restoration sites suggests that the latter may be used to establish reasonable lower limits for many parameters. They will also provide an important opportunity for determining the likely trajectory for each restoration.

Most of the salt marshes in the Delaware Bay have undergone varying degrees of disturbance in-

Fig. 4. Moore's Beach marsh, a 383 ha formerly diked marsh where "self-restoration" was initiated in 1975, and where a major storm in 1980 appears to have fully compromised the perimeter dikes.

cluding diking and invasion by *Phragmites australis*. Even without disturbance, not all salt marshes in the estuary have the same physiography, geomorphology or relative areas of vegetation, drainage, open water, and tidal flats and bars. This variability must be acknowledged and, to the extent practicable, understood early in the process of restoration planning. We anticipate that the established bounds will encompass a wide range of measured results.

Reference marshes – establishing the "bound of expectation"

Three reference marshes were selected that bracket the range of salinities and geomorphological characteristics (expected to develop) at the restoration sites to develop a monitoring program that can track restoration success. The total area is more than 2630 ha, which also places logistical constraints on sampling and analysis. Data compiled from these sites during the monitoring program will be used to establish the measurable end-points of the restorations. Mad Horse Creek (Fig. 3) is a relatively undisturbed marsh located in the oligo-mesohaline (0.5–8.5‰) portion of the estuary in New Jersey. Several portions of two previously diked areas where farming has been abandoned, Moore's Beach (Fig. 4) and Wheeler's Farm (Fig. 5), have undergone natural restoration (multiple planned or unplanned breaches of dikes) since 1980, and 1972, respectively. The latter are meso-polyhaline systems (8.5–16‰).

The reference sites differ in their ratios of the area of marsh plain:open water, and in drainage patterns. The Mad Horse Creek site has a typically sinuous drainage of relatively undisturbed marshes. The Moore's Beach site has more open water than at Mad Horse Creek, but also a general physiography resembling the undisturbed condition. Although crossed by many drainage ditches (which need to be considered when evaluating geomorphology of the channel system), the Wheeler's

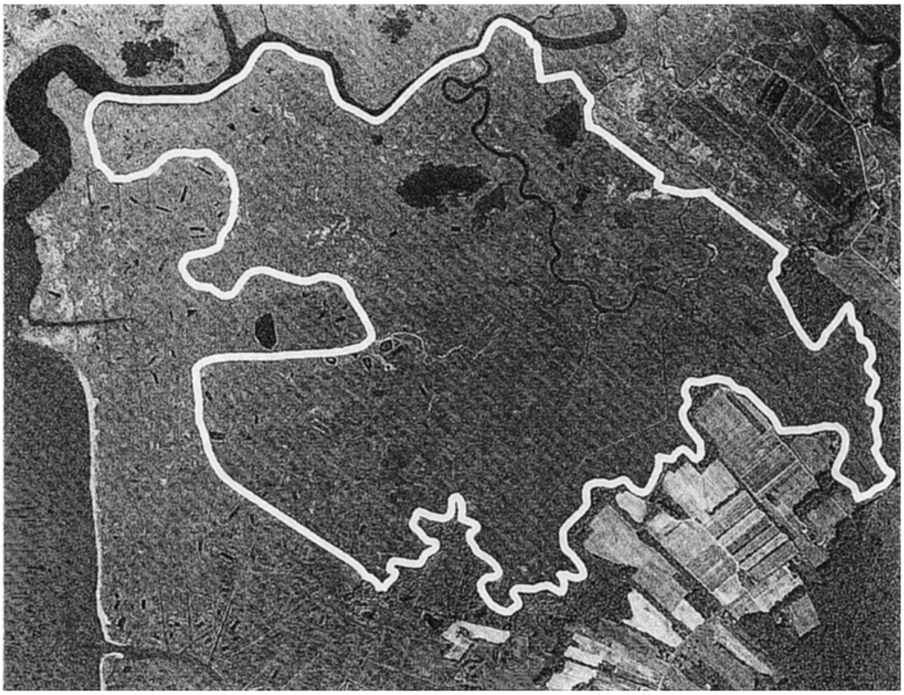

Fig. 5. Wheeler Farm marsh, a 569 ha formerly diked marsh where "self-restoration" was initiated in 1972.

Farm site appears to have less open water than the others.

The expected range of variability (Fig. 2) is the difference between the characteristics of natural marshes and the best examples of the self-restored systems. Because the planned restoration projects will be facilitated by excavating higher order channels, we believe they will recover more rapidly than the self-restored marshes.

The measurement of success

The role of the marsh drainage system

Most salt marshes are typically dissected by tidal creeks that meander and form a dendritic pattern similar in appearance to riverine systems. A relatively good understanding of the tidal drainage system use by postlarval and juvenile fishes has emerged in recent years. Many fishes will occupy the marsh fringe or marsh plain during high tides. They will congregate in subtidal channels during low tides (Cain and Dean 1976, Shenker and Dean 1979, Weinstein 1979, 1983, Weinstein *et al.* 1980, 1984, Reis and Dean 1981, Hodson *et al.* 1981, Rozas 1993, Rozas and Hackney 1983, Rozas *et al.* 1988, Smith *et al.* 1984, McIvor and Odum 1988, Hettler 1989, Kneib 1991, 1994, Rountree and Able 1992). The movement of fishes between the intertidal marsh plain, marsh edge, and shallow and deep channels is a *natural* behavior for these animals.

Thus, marsh ponds and tidal creeks are vital components of a functional salt marsh because they create aquatic habitat, and increase "edge". This is where critical exchanges occur between the marsh surface, particularly the low marsh, and open water. Most importantly, the creeks act as conduits between the estuary and the primary production that takes place on the marsh plain.

Creeks also provide subtidal refuges, and serve as a key primary nursery for early life stages of fish and shellfish (Boesch and Turner 1984). Ponds in the mid to upper reaches of the marsh serve the same functions for early life stages of resident, forage species (*Fundulus* spp., *Cyprinodon variegatus*, etc.) that provide a source of recruits to the low marsh and tidal creeks. Creeks and ponds act to create local gradients of marsh

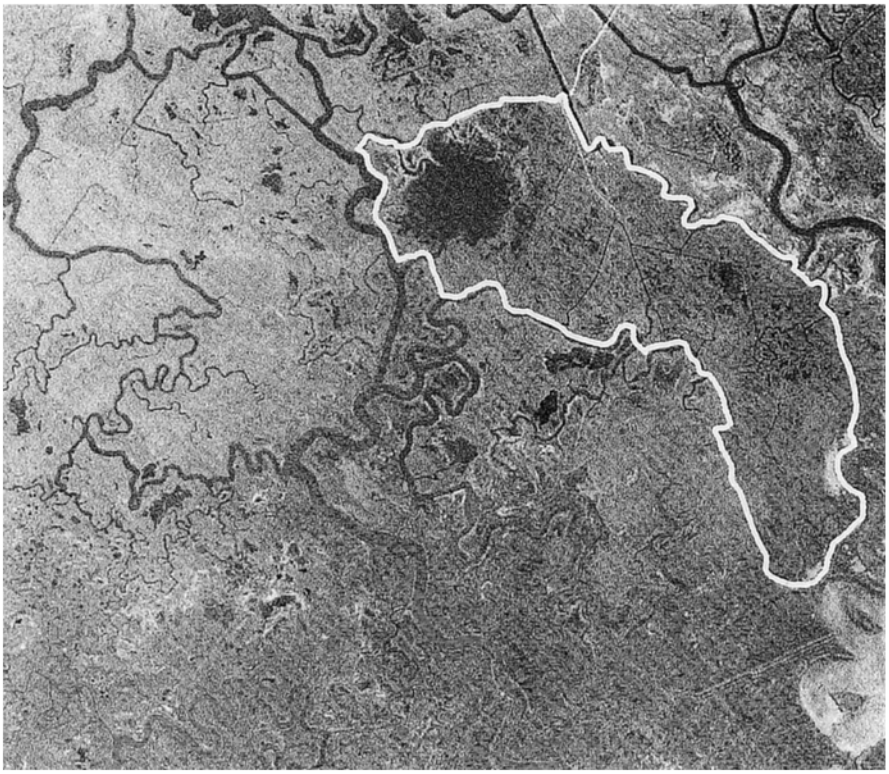

Fig. 6. Oranoaken Creek marsh, a 197 ha formerly diked marsh where "self-restoration" was initiated in the early 1970s.

types, cutting across the general marsh zonation, and adding to the mosaic of plant assemblages within each zone. The evolution of a stable dynamic equilibrium between marsh channels and plains is thus a prime consideration in wetland restoration efforts (Shreffler and Thom 1993).

Structural and functional measures of salt marshes

In increasing aquatic productivity, especially of finfishes that benefit from marshes, the following marsh features/processes are important:

1. Geomorphology and Hydrology. Tidal creeks that are subtidal at the highest stream order, and that display sinuosity and high drainage density.
2. Low Marsh. Regularly flooded marsh where exchange processes with adjacent tidal creeks (and ultimately the nearby estuary) are greatest, and where foraging species can readily reach the marsh surface.
3. Hydroperiod. A flooding-draining cycle that facilitates air entry into the marsh surface, and reduces the extent of standing water. However, small shallow ponds comprising about 1–2% of the marsh area are often found in Delaware Bay marshes (Rubino 1991).
4. Plant Coverage and Diversity. *Spartina alterniflora*, other macrophytes, benthic algae and epiphytes that colonize the marsh surface, creek banks, and mudflats are important contributors of carbon and other nutrients to estuarine consumers. The mosaic of natural plant assemblages also contributes to habitat complexity and diversity which in turn positively influences faunal diversity.

As noted above, the success of the program is closely tied to direction of restoration success (Fig. 2). Because conditions will undoubtedly differ from site to site both spatially and temporally, early success should not be measured in absolute terms but rather as a *progression* along a predictable trajectory that defines the desired char-

Table 1. Photointerpretation of historical photographs for "self-restored" marshes that were previously diked. The "Other" category included *Phragmites australis* coverage, and land features such as roadways, buildings, etc. "Open Water" included ponds, pannes, tidal creeks and intertidal mudflats.

Oranoaken Creek	*Vegetated*	*Open Water*	*Other*
Year	*% Total Marsh*	*% Total Marsh*	*% Total Marsh*
1972 (Pre-breach)	77	20	2
1978 (Post-breach)	38	62	0
1986	54	46	0
1991	57	43	0
1992	71	28	1
Moore's Beach	*Vegetated*	*Open Water*	*Other*
Year	*% Total Marsh*	*% Total Marsh*	*% Total Marsh*
1972 (Pre-breach)	56	42	2
1978 (Pre-breach)	58	40	2
1986 (Post-breach)	60	39	0
1991	65	34	1
1992	78	16	7
Wheeler Farm	*Vegetated*	*Open Water*	*Other*
Year	*% Total Marsh*	*% Total Marsh*	*% Total Marsh*
1971 (Pre-breach)	78	23	0
1977 (Post-breach)	74	26	0
1986	85	14	1
1991	84	16	0
1992	87	11	2

acteristics of that particular marsh. Features that will be measured in the reference marsh include:

1. Geomorphology. The area of creeks and ponds relative to total drainage area, the relative area of unvegetated (by macrophytes) habitat on the marsh plain, and intertidal flats and bars (as measured within the resolution limits of aerial photography); Drainage features including stream order, stream length, drainage density, bifurcation ratios and measures of sinuosity.
2. Vegetation Species composition of dominant macrophytes, measured as per cent cover and biomass; Area covered by desirable plant species, and their biomass; and, Productivity and biomass of benthic algae in vegetated and unvegetated areas on the marsh plain, and on creek banks and flats.

Ranges for these parameters can be graphed as a "family" of performance curves (Kentula *et al.* 1993), or, as discussed below, as composite variables. The rate of progress will be influenced by the disturbance history of the restoration area, and other factors. If the progress of the restoration is not satisfactory, pre-established adaptive management protocols (National Research Council 1992) will be implemented.

Revegetation of the marsh plain

There are few restoration projects where the rate and areal extent of plant recolonization have been measured. The available data suggest that where land elevation and tidal inundation are appropriate, recolonization of the marsh plain occurs at a rate of about 4%–12% per year (Bongiorno *et al.* 1974, Slavin and Shisler 1983; Roman *et al.* 1984, Bertness and Ellison 1987, Sinicrope *et al.* 1990). If a one or two year lag before vegetation is re-established is included, then we estimate that 16% to 48% of the total marsh will be capable of supporting *Spartina* spp. and other desirable vegetation within 5 to 6 growing seasons. We anticipated that there will be a temporary loss of vegetation until the root mat is partly decomposed and suitable numbers of propagules reach the area. This delay will occur over about one growing season at *Phragmites* degraded sites, and after two growing seasons in diked wetlands.

As part of the design for this project, we

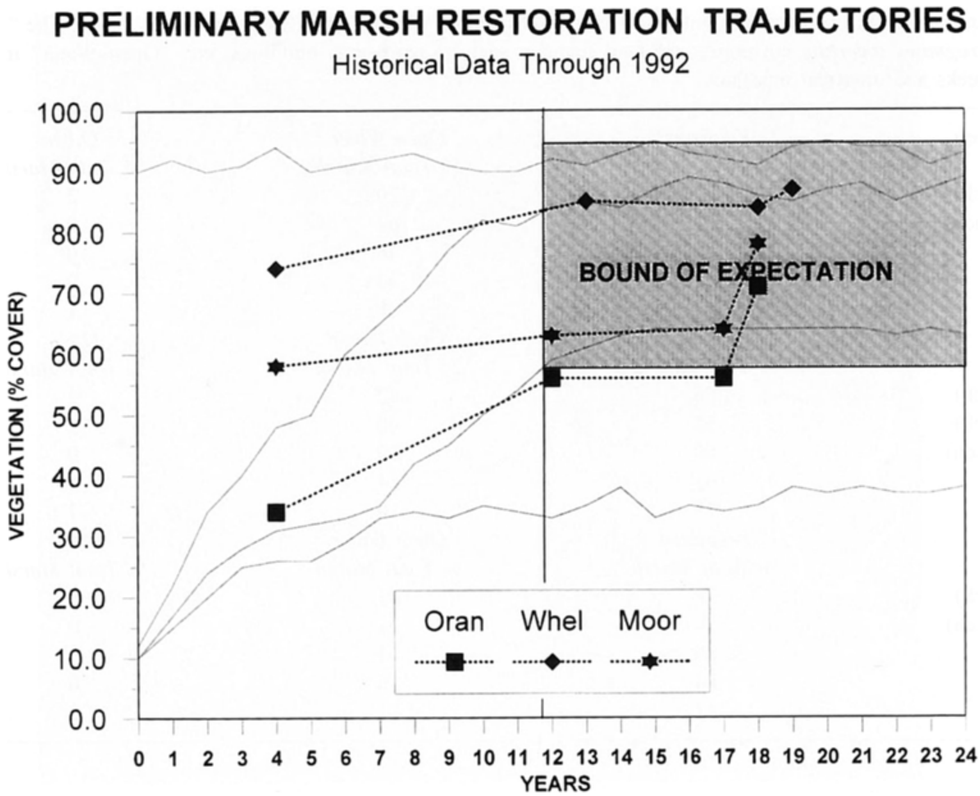

Fig. 7. Plant coverage trends measured from historical aerial photographs and superimposed on the hypothetical curves for restoration trajectories, restoration end-points.

measured marsh plain elevation and tidal heights at the restoration sites and found that most of the marsh plain is at an appropriate elevation to support *Spartina* spp. growth. Thus, the recolonization rates cited above will also apply at our sites.

To supplement these data, and to determine realistic restoration goals for each site, we examined historical aerial photography for our reference sites. False color infrared historical aerial photographs were evaluated for four locations: the minimally disturbed system at Mad Horse Creek, and three previously diked sites – Oranoaken Creek where dikes were breached in the early 1970s (Fig. 6), Moore's Beach, and Wheeler Farm. These locations overlap both the range of salinity and the physical locations of the restoration sites (Fig. 1). For each previously diked location, photographs were available for pre-breach conditions, and for at least three or four post-breach intervals spanning up to twenty years. The photointerpreted data included plant coverage, open water, and upland features including dikes, roads, etc. (Table 1). Because the level of tidal inundation varied among photographic dates, "open water" was defined as the sum of tidal channels, ponds, pannes, and flats, some of which are intertidal.

The post-breach dates shown in this table were superimposed on the hypothetical revegetation curves (Fig. 2) to determine if the projected trajectories and asymptotes were realistic (Fig. 7). Because the exact number of growing seasons post-dike breaching was not precisely known, the data were plotted in year four (the approximate average period between breach dates and the first post-breach photographs analyzed). The following conclusions result:

(1) There is generally good agreement between the photointerpreted data and the projected trajectories and asymptotes (background of Fig. 7);

Table 2. Measured values for selected marsh parameters at Mad Horse Creek and three "self-restored" marshes: desirable vegetation coverage, open water, and *Phragmites* coverage. The mean and range for the self-restored sites are shown, and all parameters are expressed as percent coverage from 1992 aerial photointerpretation. Desirable vegetation included *Spartina* spp. and other taxa.

		Desirable Vegetation Coverage	Open Water	Phragmites Coverage
Mad Horse Creek		77	19	1
"Self-restored" Sites	Mean	79	18	<1
	Range	71–87	11–28	0–1

(2) Assuming the degree of marsh subsidence at these sites was similar to that measured at the restoration sites, it appears that more vegetation survived the reintroduction of tidal flows than expected;

(3) All vegetation coverage estimates fell within or close to the bound of expectation by approximately year twelve. However, since there were eight years between the last two photographs, this coverage may have been reached sooner.

In the 1992 photographs (the most recent available), average conditions and ranges for vegetated marsh plain, and open water (including intertidal flats) were measured at all sites (Table 2). Along with the values for Mad Horse Creek, the range of values was used to establish the bound of expectation for desirable vegetation coverage. The photographs were also used to estimate the extent of open water including intertidal flats that would be expected at the end-point of restoration (see below).

Phragmites australis coverage varied significantly between sites and over time. Because groundtruth was not available for the aerial photographs, we could not distinguish *P. australis* coverage in some mixed stands. It was also difficult to distinguish it from stands of *Spartina cynosuroides*. A range of *P. australis* coverage from <1% to 15% was estimated, with reduced values in recent photographs. The average cover for all years was 2.2%.

Restoration endpoints

These values in Table 2 were used to suggest reasonable end-points both for the permitting (regulatory) goals of the restoration program. At the end of the restoration process:

(1) open water constituents of the restored sites will be ≤ 20% of the total marsh area. "Open water" in this instance includes tidal creeks (intertidal and subtidal), natural ponds, pannes, and intertidal flats;

(2) *Phragmites* coverage will be ≤ 4% of the total marsh area (≤ 5% of the vegetated area of the marsh plain; There is considerable uncertainty in the measured values using photo interpretation alone because of the lack of available groundtruthing. For this reason, approximately 5% coverage has been established as a reasonable "target" value); and,

(3) no less than 76% of the area of the total marsh will be colonized by desirable vegetation (95% of the vegetated area of the marsh plain).

A proposal for a composite criterion for measuring restoration success

The permitting goals cited above can be supplemented and extended by considering the overall project objective of enhancing aquatic production in the Delaware Bay. To optimize fisheries production requires a more refined consideration of success criteria. By modifying the habitat suitability approach of the United States Fish and Wildlife Service (Bovee 1982), it is possible to combine *all* of the relevant criteria into a single index. Like the example for vegetation coverage (Fig. 2), these values and their ranges will be plotted to establish the overall bound of expectation. The index is comprehensive in that it represent all of the desired aspects of *this* restoration project and its objective – to promote quality fish habitat.

The approach requires two steps: first a component index (CI) is calculated for each parameter (P) of interest (*e.g.*, per cent coverage by *Spartina* spp.). A single habitat value (HV) is then calculated by combining the CI scores. In this example, the critical habitat values revolve around the abil-

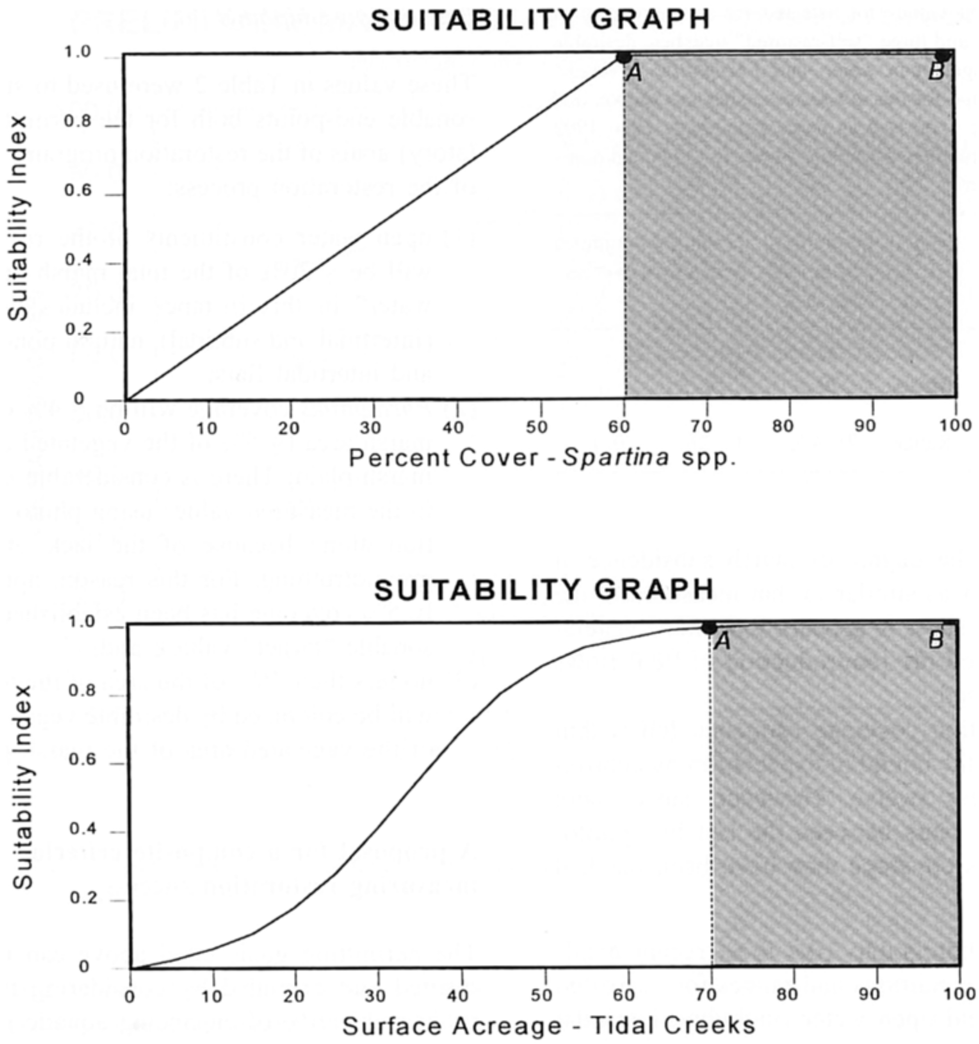

Fig. 8. Top: Percent vegetation cover, habitat suitability relationships. Points A and B represent the minimum and maximum values for this parameter (P) measured in the reference marshes. Bottom: Drainage density, habitat suitability relationships. Points A and B represent the minimum and maximum values for this parameter (P) measured in the reference marshes.

ity of the marsh to produce fish. A weighting procedure is employed to emphasize the most important habitat variables. We weighted the CI scores toward the presence of *Spartina* spp. (density and biomass), and the drainage features that maximize edge. This approach also recognizes compensatory relationships among the parameters, *i.e.*, a parameter with a low suitability can be offset by the high suitability of other parameters.

We combined variables that recognize the value of the marsh plain (including creek banks) as the major source of primary production, while at the same time serving (especially the low marsh dominated by *Spartina alterniflora*) as a nursery and refuge from predators (Kneib 1994).

Similarly, those features of the marsh drainage that maximize edge and serve as conduits for the exchange of materials were combined:

(1) Macrophytes and Algae on the Marsh Plain and/or Creek Banks
   (a) P_1 Percent cover by *Spartina alterniflora* in the low marsh
   (a) P_2 Percent cover by other desirable taxa (*e.g.*, *Distichlis spicata*, *S. patens*) in the high marsh

Table 3. Preliminary monitoring results from 1995 field surveys. Measures of dispersion around means for production estimates (gdw m^{-2} and mg C m^{-2} d^{-1} for macrophytes and algae, respectively) are standard deviations. Surface area of creeks, ponds and flats are standardized per hectare because of differences in the area of reference sites.

Site	Percent Cover (*Spartina* spp).	Percent Cover Other Taxa	Net Production Macro-phytes	Gross Production (Algae)	Surface Area Creeks (ha)	Surface Area Ponds (ha)	Surface Area Flats (ha $^{-1}$)	Drainage Density (m ha $^{-1}$)	Sinuousity
Mad Horse	56	28	369±22	5449±349	0.1564	0.0013	0.0001	52	1.32
Moore's B.	76	13	536±41	1171±119	0.0668	0.0249	0.0202	43	1.28
Wheeler Farm	78	5	485±52	1693±109	0.0711	0.0945	0.0063	36	1.23

(a) P_3 Production for *Spartina* spp. and other desirable taxa.
(a) P_4 Production of benthic algae and epiphytes

(2) Tidal Creek System Development (Geomorphology)
(a) P_5 Surface acreage of tidal creeks
(a) P_6 Surface acreage of ponds
(a) P_7 Surface acreage of unvegetated pannes, bars and flats
(a) P_8 Drainage Density (length of all channels divided by marsh area)
(a) P_9 Sinuosity (total sinuous length of the channel segment divided by straight line distance between its end-points)

Habitat Value (HV) Scoring

Habitat Value (HV) scores were used to define the target for restoration success for each restoration site. Because vegetation coverage/production and a well-developed (dendritic) tidal creek drainage are equally important components of quality fish habitat, we gave equal weight to both factors. Similarly, the parameter (P) values comprising each of the HV variables were weighted according to their importance in marsh function. Individual P values were combined as follows (for simplicity, other parameters that may be measured such as stream order, stream length, and bifurcation ratio, are not included in the calculations):

Component	*Component Index Equation*
Macrophytes and Algae on the Marsh Plain	$\dfrac{2P_1 + 1P_2 + 3[P_3 + P_4]}{9}$
Tidal Creek Development	$\dfrac{P_5 + 0.5P_6 + 0.5P_7 + 2[P_8 + P_9]}{6}$

The key marsh components were then combined as the square root of their product:

$$HV = [\text{Vegetation Component} \times \text{Tidal Creek Component}]^{1/2}$$

In this way, maximum influence is placed on low values of a given component and a zero value of any component renders the entire habitat at zero value. Thus, either a "lawnscape" of *Spartina* spp. coverage without obvious drainage features, or, an unvegetated but well-drained mudflat is an undesirable endpoint.

A simple scoring system to convert each parameter into a dimensionless habitat suitability index makes it easy to report restoration progress. Two examples follow (Fig. 8). In both graphs, points A and B represent the minimum and maximum values for P measured in the reference marshes, and, therefore, will represent the bound of expectation for the same P in the restoration marshes. The trajectories towards these bounds are obviously time dependent and can be monitored by adaptive management techniques. The HV scores for the reference marshes represents the *composite* of all asymptotic values of the individual P estimates. Restoration is considered successful when progress falls within this range.

This model will be tested and verified when the results of the monitoring program become available. However, preliminary data from the 1995 surveys are presented here (Table 3) to demonstrate differences among the reference sites and the variability of the data.

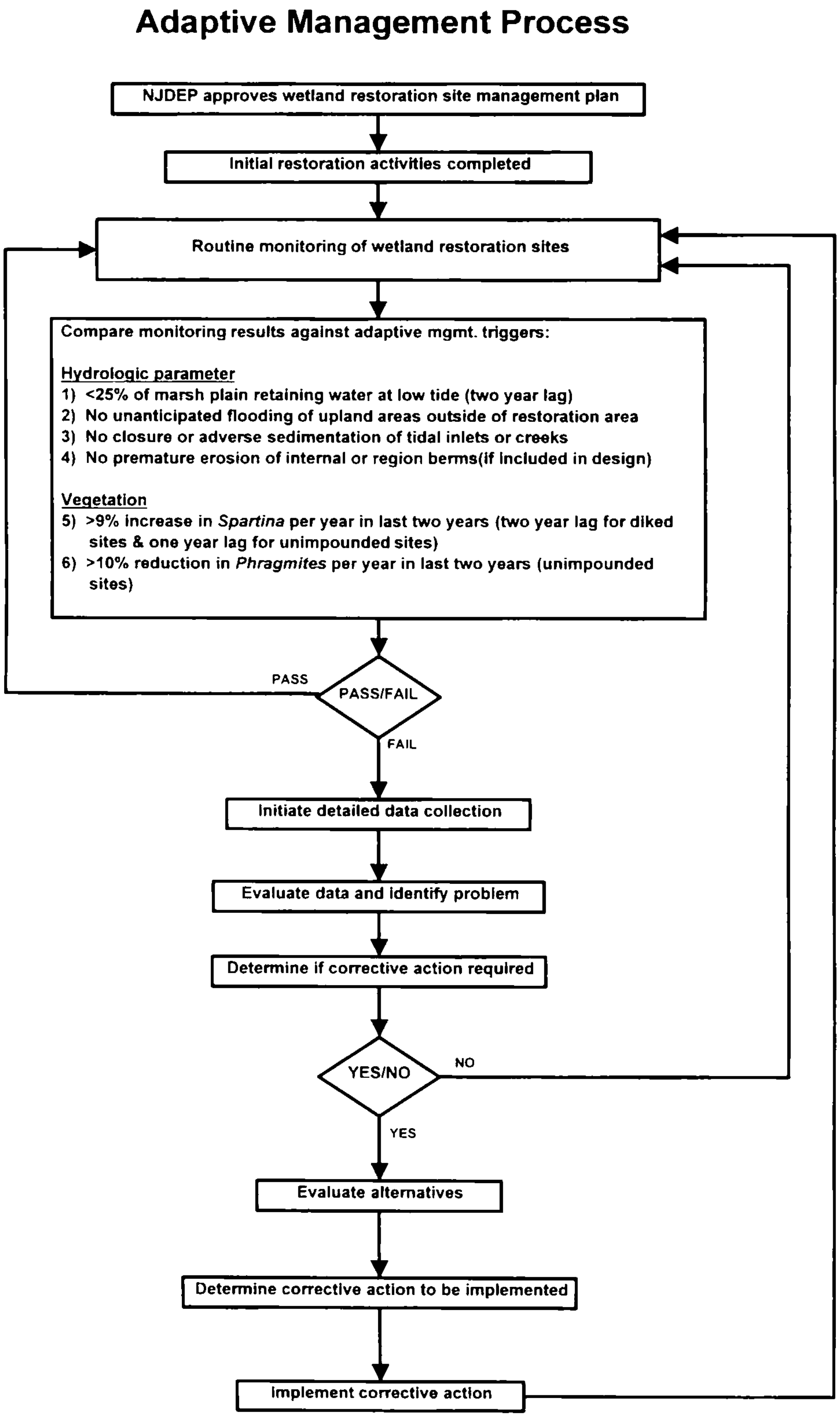

Fig. 9. The adaptive management process.

Adaptive management and corrective actions

Adaptive management is a process by which deviations from expectations can be evaluated and, when necessary, corrected (National Research Council 1992). The foundation of adaptive management is an understanding of tidal marsh ecology based on current literature and historical observations. *In situ* observation of critical parameters, comparisons, and actions are all undertaken on an ongoing, interactive basis.

The adaptive management process

The adaptive management process is illustrated in Fig. 9. Management and monitoring activities are identified that require regular site visits, including both on-ground activities and aerial surveys. When specific thresholds are not met, a series of assessment and management steps follows that includes quantitative data collection, problem identification, and 'go/no go' decisions to take corrective actions.

Threshold indicating the need for corrective measures

Thresholds set for hydrology and vegetation include:

(1) Hydrology Threshold 1: Excessive Ponding. Excessive ponding consistently present on more than 25% of the marsh plain during normal low tide.
(2) Hydrology Threshold 2: Upland Flooding. Repeated and consistent severe flooding of upland areas outside the restoration areas.
(3) Hydrology Threshold 3: Tidal Occlusion. Persistent closure of existing or engineered creeks, that impairs tidal exchange.

Relatively rapid recolonization of the marsh plain with desirable species and minimal coverage by *Phragmites australis* are primary goals. In general, re-establishment of *Spartina* spp. is expected to occur at approximately 9% per year after a one or two year lag. A reduction in *Phragmites australis* coverage of 10% per year would also assure effective recolonization by *Spartina* spp. Departures from these expected rates could trigger corrective action:

(1) Vegetation Threshold 1: *Spartina* Re-establishment. Recolonization rate threshold for *Spartina* spp. was not met in two consecutive years after the initial lag period.
(2) Vegetation Threshold 2: *Phragmites australis* loss. Failure to reduce *Phragmites australis* coverage by 10% per year in two consecutive years.

Potential corrective measures for hydrologic problems include:

(1) excavating additional higher order channels;
(2) enlarging existing higher order channels;
(3) excavating smaller order channels;
(4) providing additional breach sites on existing dikes;
(5) filling existing tidal channels (where tidal exchange is detrimental to vegetation recolonization); and
(6) stabilizing existing breaches.

Other actions may also be developed as the restorations go on. Potential biological responses include:

(1) additional herbicide applications in previously sprayed *Phragmites* areas;
(2) herbicide applications in areas not previously treated;
(3) planting *Spartina* species (seeding, plugging, or sodding) on portions of the restoration sites.

Together, these biological response activities provide effective means for corrective action should intervention be necessary (Fig. 9).

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Corresponding editor: R.E. Turner