Journal of Coastal Research	SI	40	94–108	West Palm Beach, Florida	Winter 2005

Adaptively Addressing Uncertainty in Estuarine and Near Coastal Restoration Projects

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ABSTRACT

THOM, R.M.; WILLIAMS, G.; BORDE, A.; SOUTHARD, J.; SARGEANT, S.; WOODRUFF, D.; LAUFLE, J.C. and GLASOE, S., 2005. Adaptively addressing uncertainty in estuarine and near coastal restoration projects. *Journal of Coastal Research,* SI(40), 94–108. West Palm Beach (Florida), ISSN 0749-0208.

Restoration projects have an uncertain outcome because of a lack of information about current site conditions, historical disturbance levels, effects of landscape alterations on site development, unpredictable trajectories or patterns of ecosystem structural development, and many other factors. Because of these uncertainties, project costs can rise dramatically in an attempt to come closer to project goals. All of the potential sources of error can be addressed to a certain degree through adaptive management. The first step is admitting that these uncertainties can exist, and addressing as many of the uncertainties with planning and directed research prior to implementing the project. The second step is to evaluate uncertainties through hypothesis-driven experiments during project implementation. The third step is to use the monitoring program to evaluate and adjust the project as needed to improve the probability that the project will reach its goal. The fourth and final step is to use the information gained in the project to improve future projects. A framework that includes a clear goal statement, a conceptual model, and an evaluation framework can help in this adaptive restoration process. Projects and programs vary in their application of adaptive management in restoration, and it is very difficult to be highly prescriptive in applying adaptive management to projects that necessarily vary widely in scope, goal, ecosystem characteristics, and uncertainties. One project, which included directed research and site assessments, resulted in successful restoration of seagrasses near a ferry terminal in Puget Sound and illustrates how an adaptive management process can assist in improving the outcome of small projects. We recommended that all restoration programs be conducted in an adaptive management framework, and where appropriate, a more active adaptive management approach be applied.

ADDITIONAL INDEX WORDS: *Adaptive management, estuarine restoration, seagrass restoration, coastal ecosystem restoration.*

INTRODUCTION

The purpose of our paper is to summarize growing efforts to employ adaptive management in coastal and estuarine ecosystem restoration projects. Along with the summary, we provide an example of a project from Puget Sound and list the common elements of adaptive management approaches that are emerging from various programs. Adaptive management relies on accumulation of credible evidence to support a decision that demands action (WALTERS and HOLLING, 1990), and it is designed for situations where there is significant uncertainty and a need for action. Most simply put, adaptive management means *learning by doing* in a structured rather than a haphazard way to maximize the amount learned per unit effort (WALTERS, 2001). This *accumulation of knowledge* assists in the choice of appropriate alternative actions. Although as Walters stated, "... you really don't know unless you try," the process of trying is structured to yield meaningful results.

It is amply clear that estuarine and coastal ecosystem restoration projects have significant uncertainties, and that maximizing success of restoration projects is dependent on making the right decisions on a variety of questions. Common uncertainties in coastal system restoration projects range from poor understanding of existing site conditions to funding (Table 1). Often forgotten, but no less significant, is that people can change their minds and that personnel with different ob-

04-385 accepted 20 August 2004.

Table 1. *Some potential sources of uncertainty and associated risks identified for estuarine and near coastal restoration projects (THOM, 1997, 2000; ZEDLER and CALLAWAY, 2000; WEINSTEIN* et al., *1997, 2001; TWILLEY* et al., *1999; DIEFENDERFER* et al., *in press).*

Uncertainty	Risks
Lack of adequate information on existing site conditions	Additional actions needed to prepare the site; added cost
Lack of adequate information on historical conditions	Incorrect restoration target or goal; failure of project
Lack of understanding of past and present disturbances and stressors	Disturbances and stressors may still affect site; poor performance or failure of project
Poor understanding of controlling factors (e.g., hydrology)	Incorrect or inadequate conditions for controlling factors to establish and maintain project; poor performance or failure of project
Off-site (landscape) issues affecting habitat-forming processes	Key processes required for site are not present in the surrounding landscape; poor performance or failure of project
Natural climate variability effects	Site is not resilient to natural variations in key controlling factors; poor performance or failure of project
Unpredictable trajectories for performance metrics	Expectations on performance not met; social, ecological, and economic implications on future of project
Off-site factors affecting performance (e.g., overfishing)	Expectations on performance not met; social, ecological, and economic implications on future of project
Implementation mistakes	Poor performance or failure of project; delayed development; added costs to remedy
Funding uncertainties	Delayed development; expectations on performance not met; social, ecological, and economic implications on future of project
Social uncertainties	Expectation on performance change; social, ecological, and economic implications on future of project

jectives join projects. These *social* uncertainties can also affect the progress and outcome of a restoration project.

Because many proposed and active restoration projects are costly, maximizing the probability of success is critical (THOM, 1997, 2000; WEINSTEIN *et al.,* 1997). Large regional restoration and monitoring programs are currently embracing the concept of adaptive management (WEINSTEIN *et al.,* 2001; BUSCH and TREXLER, 2003; OGDEN *et al.,* 2003). Incorporating adaptive management into coastal system restoration projects involves three fundamental elements: a clear goal statement, a conceptual model, and a decision framework (THOM, 2000). The goal "drives" the design, and the conceptual model explicitly summarizes the state of understanding about the system to be restored. The framework specifies uncertainties and approaches for dealing with them. The framework also provides the evaluation process, the decision triggers, and alternatives pathways. The process does not have to be complex or costly, but it needs to be well thought out. In addition, there must be a continuous commitment to the process throughout the life of the project (THOM, 1997). Finally, the science of restoration benefits from the broad dissemination of information that includes lessons learned. Project reports are often difficult to access, and they serve little purpose to the science of restoration. However, there are exemplary publications that contain a wealth of information useful to a broad audience of coastal restoration planners. For example, syntheses of seagrass restoration (FONSECA *et al.,* 1998) and of tidal marsh restoration (ZEDLER, 2001) detail the state of the knowledge in their specific areas and identify the uncertainties that can lead to failure of projects; they also provide tested solutions that effectively increase the certainty of restoration projects.

EXAMPLES OF PROGRAMS

Details on eight aspects of four programs listed in Table 2 are summarized from unpublished reports as well as from presentations and our discussions with key individuals involved in each of the programs. These include a nationwide aquatic ecosystem restoration mission (U.S. Army Corps of Engineers [USACE]) and large regional programs focused on tidal wetland restoration (Mississippi River Delta) and on restoring water quality (Puget Sound). The adaptive management approaches we summarize represent a set of programs that vary in focus, scale and maturity.

Puget Sound's program is the most mature program listed in Table 2. Commercial and recrea-

Table 2. *Summary of four adaptive management programs.*

	Puget Sound Shellfish (Puget Sound Water Quality Action Team)	Mississippi Delta Marshes	U.S. Corps of Engineers	Clinton Eelgrass Restoration
State of Development	Dynamic, relatively mature regional water quality program with a high degree of public involvement; began in late 1980s	Rapidly growing, large regional program with focus on coastal marshes; began in mid-1990s	Emerging national program with roots in water management; not implemented yet	Began in 1997
Scope/Scale	Sound-wide to local (*i.e.,* neighborhood) scales	Tidal marshes and swamps over the entire delta	Aquatic ecosystems associated with U.S. "navigable waters"	Site specific project; ~1 ha eelgrass restoration near Clinton Ferry Terminal
Goal(s)	Eliminate harvest restrictions caused by microbial contamination	Reverse loss of wetlands	Reverse damages to aquatic systems from past projects	No net loss of eelgrass due to terminal expansion; evaluate new technologies
Conceptual Model	Includes sources, modes, and sinks of contamination	Stressor (sediment and nutrient inputs) linked clearly with marsh loss	Will be developed for specific projects; have models used in standard project planning process	Specific for factors affecting eelgrass at the terminal
Monitoring	2 performance measures; 7 environmental indicators; 3 biennial outcome measures	Extensive, site-specific; basin-level evaluation reports; projects have a 20-year life span; assess trajectories, not pass/fail	No formal treatment as yet; monitoring is conducted on a project basis to various levels; cost-shared with local sponsor at ≤1% of initial project cost	Annual, eelgrass area, eelgrass density, eelgrass abundance, salmon prey density; ten year monitoring of each plot
Management	Scientists, industry, and community representatives assess progress using biennial outcome measures, make recommendations, communicate to public	Interdisciplinary teams meet every 6 months to review data and make recommendations; contingency plans in place	Informal; no programmatic treatment yet	Review results annually with agencies; adapt project to assure success
Assessment	1987 emphasized watershed planning; 1991 implemented shellfish closure response strategies; 1994 emphasized strong land use and shoreline plans to protects sensitive beds; 1996 instituted early warning system sampling to target corrective actions	Have contingency plans and procedures to expedite repairs; proposed Coastwide Reference Monitoring System (CRMS) should provide landscape context	Guidance allows for adaptive management for large, complex projects with uncertain outcome; nothing formal yet; have contingency plans on some projects	Results verify predictions of success for each plot; total abundance a better indicator of no net loss than mean shoot density; reference plots are not ideal match to restoration plots
Specific Uncertainties	Improvements threatened by relentless increase in population; offsite factors of fishing pressure; funding uncertainties	Vandalism of structures; enormous cost of program; large projects have failed	Yet to be determined, but all potential uncertainties as indicated in Table 1	Storm-forced sediment redistribution; time for eelgrass development; damage to donor stocks; climate-driven effects on eelgrass

tional shellfishing are major activities in Puget Sound. Contamination of shellfish by microbial pathogens is a major threat to shellfishing in the Sound. There is uncertainty in the sources of contamination, which impedes the efforts to reduce health concerns. Case studies are used to assess whether watersheds, septic, or marine discharges are contributing to the problem. The Puget Sound Action Team (PSAT) is involved in neighborhood-scale projects; community-scale programs and processes; and regional, state, and national planning and policy-making (PSAT, 2002, 2003). In all instances, adaptive management is applied continually. Key points relevant to adaptive management that have been learned by PSAT are as follows:

(1) It is critical to carry out programs through local planning processes, such as watershed, land use, and shellfish-closure-response planning.
(2) Local programs, such as those addressing storm water, onsite sewage, and shoreline management, are dynamic and are constantly adjusted to reflect changing conditions and new information; that is, they must adapt to ecosystem and social changes.
(3) The work is essentially unending, because the types of problems are rarely fixed or permanently solved; that is, the adaptive management process is accurately depicted as a circular process.
(4) The rapidly growing Puget Sound population represents the key uncertainty regarding the ability of actions to reduce contamination and further environmental degradation; it drives social and economic change in a finite and already stressed ecosystem.

The Mississippi Delta Marsh Restoration program is the second oldest program listed in Table 2, and represents a trend to develop massive ecosystem restoration programs in the U.S. Other planned or implemented programs on a similar scale include the Florida Everglades, San Francisco Bay (California Federal Bay-Delta Authority [CALFED]), and the Puget Sound Nearshore Ecosystem Restoration Program (PSNERP). On the order of 80% of the loss of coastal wetlands in the U.S. occurs on the Mississippi River Delta in the state of Louisiana. Presently, because of a variety of factors, wetlands are lost at a rate of 65–90 km^2 y^{-1}. Because of the low-lying topography, wetland loss also threatens roads, pipelines, and the general infrastructure of the region. The Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA), Public Law 101-646, was passed in 1990 to address this problem. The primary strategy for restoring wetlands is to divert fresh water containing nutrients and sediments into wetland areas adjacent to the Mississippi River. In addition, barrier islands and other shoreline protection measures are being implemented to protect vulnerable leading edges of the marsh. Between 1994 and 2001, 60 projects were constructed covering approximately 243,000 hectares (RAYNIE and VISSER, 2002). Projects are to be monitored and managed for 20 y. The CWWPRA adaptive management program has developed several "program recommendations" based on the information gathered to date (Table 3). These recommendations relate to the major aspects of a restoration program: goals, project management, construction, operation and maintenance, monitoring, and reporting. Hence, the CWWPRA program is incorporating timely, science-based adjustments into the restoration projects.

Traditionally, the USACE flood-control efforts have been adaptively managed. For example, the agency's dam operation in the Columbia River basin has been adaptively managed for several years to meet a number of competing demands for water. Notably, the Adaptive Environmental Assessment (AEA) and modeling method has been applied in a multi-agency restoration effort in the Kootenai River system in Montana, Idaho, and British Columbia (WALTERS, 2001). Based on the AEA, operation of the USACE's Libby Dam was considered a primary influence on the Kootenai River and fish populations listed there under the Endangered Species Act.

Faced with potentially huge environmental restoration projects and programs that could exhibit all of the uncertainty types listed in Table 1, the USACE adaptive management program could become one of the most prominent programs in the nation. However, based on a review by one of us (LAUFLE), the process is currently informal: there is no programmatic treatment of adaptive management and monitoring for ecosystem restoration within the USACE Civil Works program. Since 1986, the USACE has operated under legislation that provides for aquatic ecosystem restoration as a new mission. Most notable and actively applied are Section 1135 of the Water Resources Development Act (WRDA) of 1986 and Section 206 of WRDA 1992. The USACE's guidance (USACE,

2000) for implementation of these authorities addresses adaptive management. It specifically allows for use of adaptive management for large or complex, authorized projects with uncertain outcomes.

EELGRASS RESTORATION EXAMPLE

Background

Eelgrass (*Zostera marina L.*) is one of over 50 species of seagrass that grow in shallow marine and estuarine waters in most regions of the world (SPAULDING *et al.,* 2003). Its value as habitat for fish and invertebrate species, as well as for other functions, is well documented (e.g., EDGAR *et al.,* 2001). Eelgrass has suffered losses globally because of coastal development and will continue to be threatened into the foreseeable future. Some of the earliest restoration projects have involved seagrasses (reviewed in FONSECA *et al.,* 1998). In Puget Sound, eelgrass is considered a critical habitat for fisheries support and is therefore protected. Restoration projects have met with variable success, and methods to improve success are needed (THOM, 1990). The uncertainties associated with eelgrass restoration are site requirements, plant handling, transplanting methods, and post-planting disturbances. Since 1996, some of us (THOM, WILLIAMS, BORDE, SOUTHARD, SARGEANT, WOODRUFF) have conducted an eelgrass restoration project located at the Clinton Ferry Terminal in central Puget Sound. The project is part of a compensatory mitigation program to address impacts from enlarging and rebuilding the terminal. Because of the complexity of the site and past eelgrass restoration failures (THOM, 1990), the eelgrass restoration project is being conducted in an adaptive management framework. Further, the Clinton Ferry Terminal project was to provide a model for addressing environmental issues associated with reconstruction of 19 other aging terminals in Puget Sound. The adaptive approach, described more fully below, followed the three essential elements—goal setting, conceptual model development, and design and implementation—of an adaptive management framework (THOM, 2000).

Goal Statement

The primary goal for the project was as follows:

No net loss of eelgrass because of the terminal reconstruction—This goal clearly set the standard that, by the time the project was completed, there would be at least as much eelgrass present at the site as existed prior to construction.

The performance criterion established by the resource agencies relative to this goal was that by the end of 5 y, eelgrass density (*i.e.,* number shoots m^{-2}) in the restored plots must be at least 85%

Table 3. *Program level recommendations for Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) Mississippi Delta marsh restoration projects (RAYNIE and VISSER, 2002).*

Component/Program Level Recommendations
Goals
Develop and define project goals early in the process.
Avoid success/failure mindset, which leads to vague goals and objectives.
Define targets and trajectories to evaluate project performance over the 20-y life of the project.
Project Management
Create project management team:
• involve personnel in all aspects of the project
• include two academic advisers
Encourage institutional memory.
Improve communication.
Construction
Control construction and operation (CWPPRA):
• follow planned construction designs and operation schedules (landowners and local governments)
• revise land-rights agreements
• closely supervise construction contractors
Operation and Maintenance
Avoid vandalism of structures:
• engineer structures to make unauthorized changes impossible
Develop contingency plans:
• plan for extreme environmental and meteorological events
Design procedures to expedite repairs.
Monitoring
Put project performance in context of the larger landscape, not of one reference site:
• provide context via proposed Coastwide Reference Monitoring System (CRMS)
• provide basin-level evaluation reports
Base budget monitoring on data necessary to adaptively manage and evaluate the project, not on project type:
• de-emphasize success/failure mind set
• improve coordination between monitoring and operation/maintenance activities, and data collection
Reporting
Use the final report along with project-specific reports, recommendations, and supporting documents for guidance during all phases of future project planning and implementation.

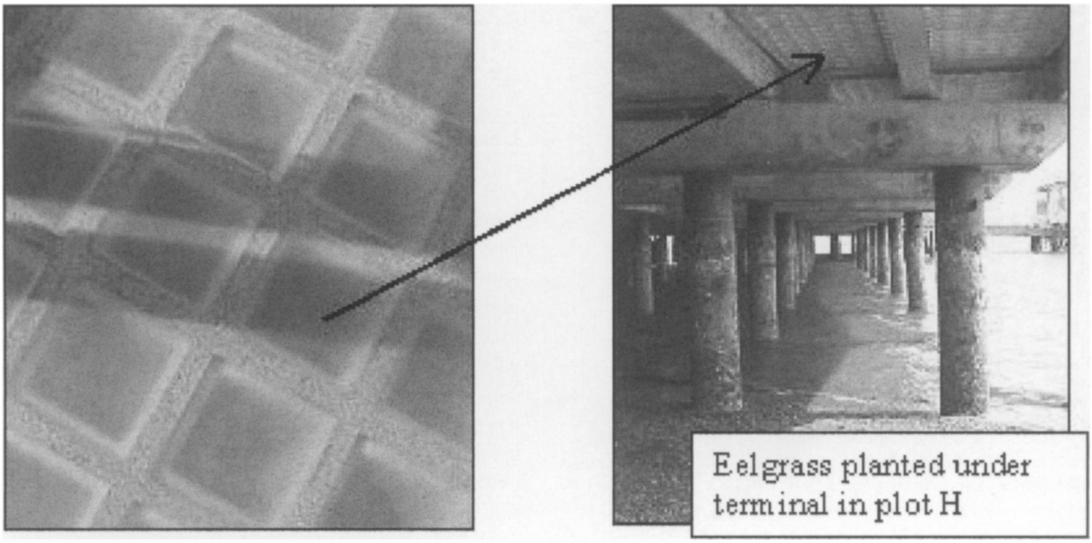

Figure 1. Glass blocks installed in walkway at edge of the Clinton Ferry Terminal.

that of the reference plots. A secondary goal for the project was to evaluate new concepts in mitigating shading effects. This goal was established because most of the other 19 terminals in the system required replacement within the next decade, and this project would evaluate methods to reduce eelgrass loss that could be implemented at these other terminals. No performance criterion was set for the secondary goal other than provision of data on the effectiveness of light enhancement under the dock by incorporation of glass blocks in the walkway on the south edge of the terminal (Figure 1).

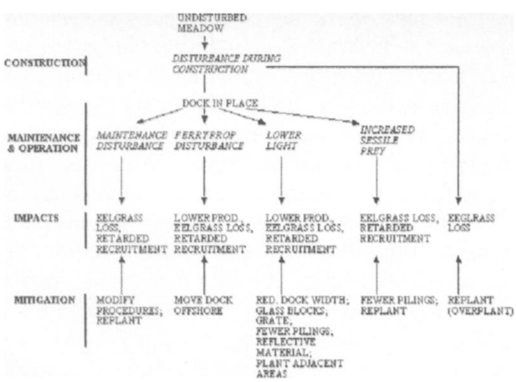

Figure 2. Site assessment disturbance-stressor model for eelgrass at the Clinton Ferry Terminal in Puget Sound. The five stressors (italics) are: initial construction, maintenance disturbances, propeller wash, lower light (shading), and increased sessile prey which leads to greater numbers of bioturbator species.

Conceptual Models

Research focusing on the effects of terminal structure and vessel operations on eelgrass revealed at least five major stressors on eelgrass (THOM *et al.,* 1997; Figure 2). It was obvious that shading would affect the plants, but less obvious were the impacts from initial and maintenance disturbances as well as from the light reduction caused by turbidity from propeller wash. Even more surprising was the potential effect of bioturbators, including large sea stars (*Pychnopodia helianthoides*) and Dungeness crab (*Cancer magister*). The pilings of the terminal harbored dense mussels and barnacle populations that were preyed upon by the sea stars and crab. The piles of shell and test debris that accumulated under the terminal may have created habitat for enhanced settlement and survival of the crab, as documented by DUMBAULD *et al.* (1993) in other areas. Divers near the terminal noted sea stars as dense as 15 m^{-2}, and hundreds of crabs. Both crab and sea stars were observed foraging and burying at the edge of the eelgrass meadows near the terminal, thereby disturbing and disrupting the mead-

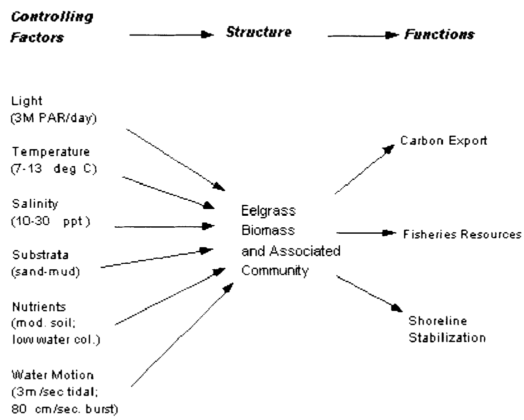

Figure 3. Conceptual model of factors controlling eelgrass growth in Pacific Northwest systems. (Data from PHILLIPS, 1984; THOM, 1995; THOM *et al.,* 1998.)

ow and inhibiting regrowth of eelgrass into areas disturbed by construction and maintenance operations. The mitigation strategies addressing each of these impacts were developed based on the findings of the research program (Figure 2). Mapping and diver assessments also showed that there were a number of bare patches with no eelgrass that were difficult to explain. We suspected that past disturbances or periodic, intense wave events were important causal factors.

Our evaluation of factors affecting eelgrass growth in Puget Sound along with a review of published information allowed us to develop a second conceptual model (THOM, 1995; THOM *et al.,* 2003; Figure 3). This model formed the basis for an evaluation of the lack of eelgrass in some areas where we thought it should be, and the prediction of the probability of success of eelgrass restoration at sites near the terminal. This site-selection approach is similar in intent to that developed by SHORT *et al.* (2002) for sites in New England.

Based on the questions from terminal design engineers and on the knowledge that lower light would mean less eelgrass, we tested several technologies to enhance the amount of light under the terminal (BLANTON *et al.*, 2002). Among the most promising technologies was the use of glass blocks (Figure 1). The glass blocks, which passed approximately 60% of the incident photosynthetically active solar radiation (PAR), were placed in the walkway along the southern edge of the terminal deck and over the portion of the bottom where eelgrass occurs (Figure 4). To reduce potential slipping by passengers, the glass was roughened, and a clear plastic roof and wall were constructed in the same portion of the walkway to keep it dry.

Uncertainties

A total of 14 transplant plots were identified based on the research project (Table 4; Figure 4). Because we were unsure of the reason for the absence of eelgrass from some of these plots, and because some of the plots (e.g., those under the glass blocks and under the terminal) were experimental, we assigned a qualitative prediction of low, medium, and high chance of success for the plots (Table 4). By stating these predictions *a priori,* we acknowledged the uncertainties and we were able to evaluate these plots as experimental tests of our ability to understand the factors affecting eelgrass survival.

We dealt with five primary sources of uncertainty. First, the size of the planting area would overcompensate area to be lost by a 9:1 ratio. Hence, meeting the goal in most of the transplant plots should have resulted in a net gain in eelgrass. Because this project was to provide information useful to other ferry terminal projects, experimental areas were established that had low or moderate probability of succeeding, but were included to evaluate questions such as whether glass blocks could enhance light through terminals, whether propeller wash was truly the cause of eelgrass loss at the deep portion of the meadow, and whether drifting woody debris and scour were the cause of eelgrass loss in shallow areas near the terminal. Second, the first phase of planting was conducted ~18 months prior to terminal reconstruction in an area approximating 100% of the 320-m^2 area to be covered by the new terminal deck. This provided "up-front" compensation, thus minimizing functional losses during the time between terminal reconstruction and restoration. Third, there was uncertainty regarding damage to the donor beds. We salvaged 5000 shoots of eelgrass from the area to be destroyed during construction and grew these in seawater tanks to approximately 29,000 shoots within 2 y. This stockpile supplied all the required transplanting material as well as material needed for any supplemental plantings. Fourth, we anticipated that construction activities would have an adverse impact on eelgrass restoration efforts. Hence, we staged plantings to follow as closely as possible after construction phases near the resto-

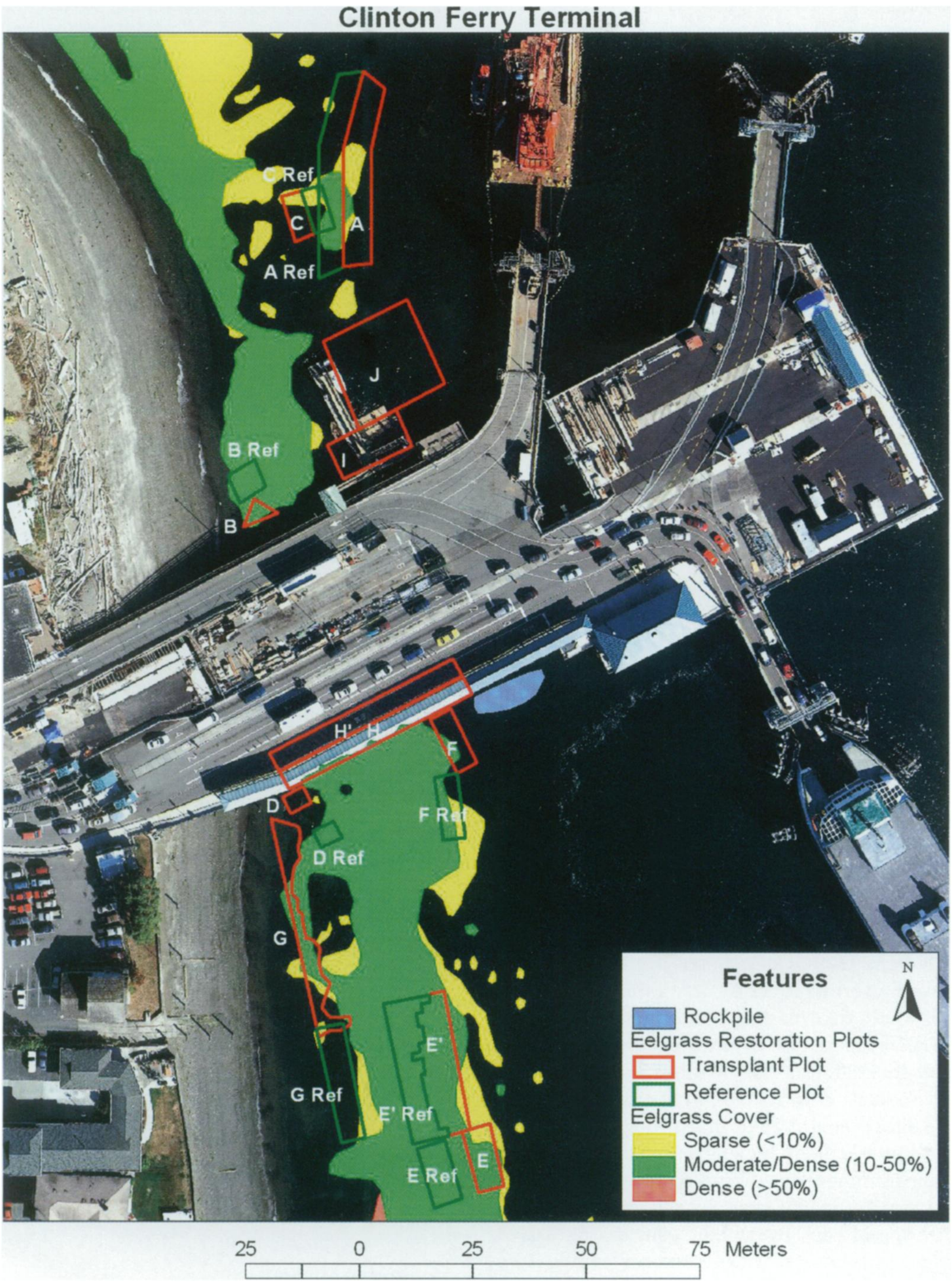

Figure 4. Clinton Ferry Terminal showing transplant and reference plots. Map of eelgrass based on 2003 side scan sonar mapping. Plots B‴ and B⁗ are not shown but were orginally located under the terminal (see also Table 4). Glass blocks are located over plot H.

Table 4. *Conclusions from the first seven years of the project, and recommendations. Included are the years since planting, estimated area of each plot, percent of the plot planted, mean eelgrass shoot density as of summer 2003, percentage of the performance criterion met by this density, and predicted future performance of the plot as of 2003. Predicted performance ranks were L = low, M = moderate, and H = high. (See also Figures 4 and 5.)*

Plot	Age (yrs)	Estim. Area (m^2)	Planted (% of area)	Mean Dens. (no. m^{-2})	Perform. Criterion (%)	Predicted Perform.	Conclusions	Recommendations
A	7	3,422	28	14.6	28	L-M	Marginal site; at carrying capacity	Do not fully plant
B	7	823	7	161.6	91	M	Highly viable site; should continue to flourish	No action
C	7	152	101	40.1	97	H	High potential with removal of disturbance	Enhance with plantings; expand to adjacent area
D	2	61	108	1.0	3	H	Viable site, but highly susceptible to sediment movement	No action
E	7	762	123	58.1	47	M	Viable site; density will remain somewhat low	No action
E′	4	(incl. in E)		69.1	56	M	Viable site; density will continue to increase	No action
F	2	213	108	3.0	38	M	Marginal site; density will reach low but stable level	No action
G	6	762	75	160.1	215	M	Highly viable site; wave disturbance may be an issue	No action
H	2	658	103	8.8	NA	L-M	Experimental; should persist at low level	No action
H′	2	549	124	0.3	NA	L	Experimental; may not persist	No action
B′	—	1,408	—	—	—	L	No chance of survival; located under terminal	Do not plant
B″	—	640	—	—	—	L	No chance of survival; located under terminal	Do not plant
B‴ (I)	—	271	—	—	—	H	Moderate to high potential	Expand size and plant; coded new plot I
B⁗ (J)	—	360	—	—	—	H	Moderate to high potential	Expand size and plant; coded new plot J

ration plots. The second and third phases of planting were conducted in 1998 and 2001, following completion of construction on the south side of the terminal, and the final phase of planting in 2003 followed completion of construction of the north side of the terminal. Fifth, it was uncertain how long it would take for eelgrass to establish and stabilize. Most eelgrass monitoring programs have been conducted over short periods of 1–2 y (THOM, 1990; FONSECA *et al.*, 1998), and it was suspected that eelgrass might take much longer to build a stable and resilient biomass. In addition, a 5-y monitoring time-frame, often required in more recent projects, is untested in the region. Hence, monitoring of each transplant plot and its paired reference site was planned to occur over a 10-y post-planting period. This period would allow eelgrass plantings to mature and would likely span at least one or two climatic anomalies (*i.e., El Niño* events) known to affect eelgrass (THOM *et al.*, 2003).

Planting Methods

In all cases, eelgrass was planted as bare root bundles consisting of four shoots per bundle that were anchored in densities of five bundles per square meter. Anchoring was initially accomplished by using wooden tongue blades to protect new transplants from occasional strong currents (up to 3 m s^{-1}) and waves at the site. We found after Phase 1 planting that Dungeness crab could unbury eelgrass anchored with tongue blades. Hence, subsequent plantings incorporated U-shaped "landscape" staples, which penetrated deeper into the sediment and appeared to reduce crab damage.

Monitoring Methods

Each transplant plot (except H and H′, which were established only to determine whether eelgrass could survive) had a paired reference plot (Figure 4). Selecting reference plots was difficult, because physical conditions can differ over short distances. We knew from studies at Clinton and other areas in Puget Sound that eelgrass density can vary significantly with a small change in depth (*i.e.*, $\Delta \approx 0.3$ m; THOM *et al.*, 1998). Each plot was quantitatively sampled in summer. Underwater photographs and videography were used to document the condition of the plots. All sampling was accomplished using SCUBA. A 0.25-m^2 quadrat was used to sample eelgrass metrics in each plot, with a sampling density of 3 quadrats/8 m^2. Quadrats were positioned systematically in each plot relative to a random start point to assure full coverage of the plot and, at the same time, to acquire an unbiased sample. The number of shoots in each quadrat was recorded, and the length of the longest leaf on a single shoot located in the center of each quadrat was recorded. Any disturbances obvious during the summer sampling that could have affected plant survival were recorded. In addition, qualitative observations were made in autumn, winter, and spring, primarily to identify any stressors (e.g., anchor chains, sunken logs, storm damage) that could have affected the results but that would not necessarily have been apparent in summer. The area was mapped in 2003 using side scan sonar and underwater videography to fully document the location and coverage of eelgrass within 100 m on either side of the terminal. (Figure 4)

Adaptive Management Framework

The adaptive management framework consisted of the following elements: predictions of probabilities of success (Table 4); a monitoring program to assess progress towards the goals; agreement to make adjustments to meet goals based on knowledge gained through monitoring; annual meetings with resource agency representatives to review the data and decide on adjustments; and dissemination of the results of the work through regional and national meetings, reports, and peer-reviewed publications. A key distinction was made between goals and performance criteria. Although the performance criteria were established to indicate progress toward the goals, the performance criteria (as well as the goals) could be adjusted, if justified by monitoring results. Dissemination of results was particularly important, because one goal was related to evaluation of the technologies that may be applicable to other terminals and to overwater

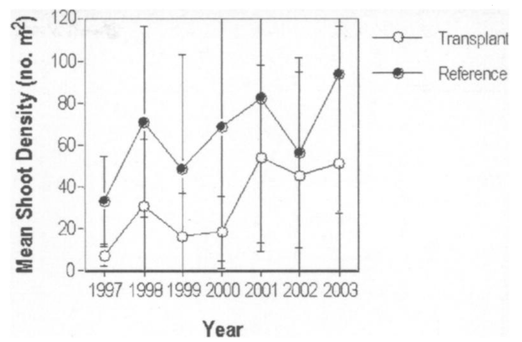

Figure 5. Mean eelgrass shoot density at Clinton Ferry Terminal for all transplant plots and all reference plots. The 80% confidence limits are shown around the mean densities.

structures in general. In this way, this project would contribute to regional and broader learning.

Resource agencies, including the Washington State Departments of Fish and Wildlife (WDFW) and Ecology (WDE) and the National Oceanographic and Atmospheric Administration (NOAA) Fisheries group, were actively involved from the outset in reviewing and commenting during the development of the original research program and during the monitoring and adaptive management program. This involvement was continued through their participation in the annual project meetings where adaptive decisions were made.

Transplanting Results

As of summer 2003, shoot density (63.5 shoots m^{-2}) averaged over all transplant plots was 68% of the average reference site mean density (93.6 shoots m^{-2}), and 80% of the performance criterion (performance criterion = $93.6 \times 0.85 = 79.6$ shoots m^{-2}) density (Figure 5). However, because of the high degree of variance, illustrated by the large confidence limits around the means between the plots in each category (Figure 5), it is not possible to determine how well transplants are doing relative to the performance criterion.

The degree of variability between individual plots is illustrated in Figure 6. In most cases, density varied annually in a similar direction at both the reference and transplant plots. The large increase in eelgrass density between 1997 and 1998, with a rising trend continuing to 2001, may have been linked to a post-*El Niño* resurgence of eelgrass generally seen in the Pacific Northwest

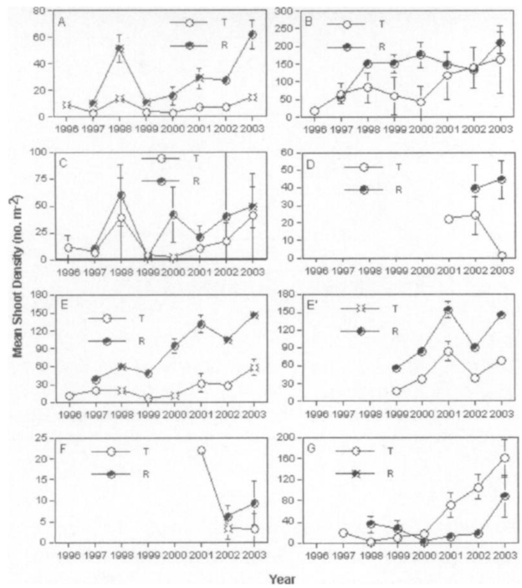

Figure 6. Mean eelgrass shoot densities for the eight transplant plots (T) and their paired reference plots (R) at the Clinton Ferry Terminal. The 80% confidence limits are shown around the mean densities where they exceed the diameter of the point. Plot locations are shown in Figure 4.

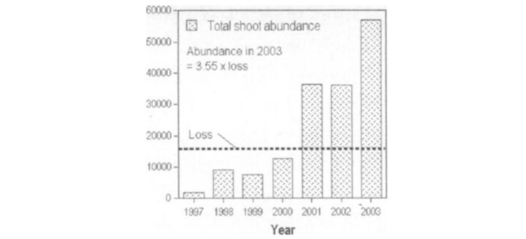

Figure 7. Total shoot abundance in all transplant plots between 1998 and 2002 compared with number of plants lost because of the project. Loss from terminal construction was estimated to be approximately 16,000 shoots.

(THOM *et al.*, 2003). Reference Plots B, E, and E′ exhibited increased densities of on the order of three- to fourfold between 1997 and 2000 or 2001 (Figure 6). These plots held the greatest densities among all the plots planted, and changes in mean density for all plots are attributable primarily to these plots. These plots also contain some of the most robust areas in the meadows surrounding the terminal. We strongly suspect that they were responding to natural climate-driven variation during the period, as were the meadows in outer coast estuaries.

Eelgrass density in individual plots showed varying levels of performance (Figure 6). Eelgrass in Plot A, one of the deepest plots, showed limited success relative to a shallower reference site. After 7 y, we concluded that eelgrass in this plot will not get any denser, but will persist in the long term. In 2002, we reached a similar conclusion regarding Plot E. However, eelgrass density doubled between 2002 and 2003 in Plot E. Plot B eelgrass, after undergoing a decrease in 1999–2000, was as dense as the reference plot by 2001. Plot G eelgrass flourished relative to the reference plot. The reference plot, which underwent damage due to winter storms and perhaps small boat activity in 1999–2000, increased density on the order of fourfold between 2002 and 2003. Newly planted Plot D suffered severe damage from sediment deposition during the winter of 2002–2003. Eelgrass in Plot F, which was planted at a density greater than that of the reference plot, was tracking toward reference plot densities after 1 y.

Only a small portion of the eelgrass planted under the glass blocks was surviving (Table 4). Monitoring of PAR under the glass blocks showed that light was enhanced only approximately 10% above that found under the solid terminal deck. Apparently, the scarring of the blocks and installation of the plastic roof and wall decreased light passage more than expected. We did note that the light-dark edge contrast was softened under the glass blocks (Figure 1).

Overall eelgrass abundance in the transplant plots was greater by 2001 than the abundance estimated to exist at the site where eelgrass was lost due to construction (Figure 7). We estimated that approximately 16,000 shoots existed in the area where terminal expansion would occur, and by 2003 there were over 56,000 shoots in the transplant plots, resulting in approximately a 3.5:1 shoot replacement ratio. The total area where viable eelgrass exists in transplant plots covers about 1300 m^2, which is a 4.1:1 replacement of the area lost.

Monitoring Duration

In four of the eight plots, the number of newly transplanted shoots decreased in the first year, then increased by the second year (Figure 6). This may be a response to initial die-off often reported for newly planted systems, and probably reflects a period of adjustment by the plants, especially a clonal plant such as eelgrass. However, density increased at the other four plots, which may indicate that these plots contained near optimal conditions for eelgrass.

It appeared that, after 4–7 y, eelgrass density was not going to change dramatically in the deeper plots, A and E, which may indicate that the carrying capacity for eelgrass had been reached in these plots (*i.e.*, plots A, E; Figures 6A, 6E). However, in shallow plots, B and G, density was stable between years 1 and 4, and increased substantially after year 4 (Figure 6B). We found that survival after 4 y was correlated with survival after 1 y. This was especially true for the deepest plots (A, C, E, E′), where the correlation coefficient between first- and fourth-year survival, as a percentage of the initial planting density, was 0.93 and followed the equation below:

$$y = 1.869x + 38.02$$

where

y = survival at 48 months as a percentage of initial planting density
x = survival at 12 months as a percentage of initial planting density

This type of relationship helps develop predictive tools for restoration. For example, the results from eelgrass test plantings after 1 y can be used to predict the long-term survival and density at that site. This test planting would save cost by eliminating plots that showed low first-year survival (SHORT *et al.,* 2002).

Issues with Paired Reference Sites

As mentioned above, it was difficult to define reference sites that exhibited the exact physical characteristics of the transplant plots. One primary difference between many transplant plots and their corresponding reference plots was depth (Figure 8). Depth is a primary factor affecting eelgrass density. Maximum shoot density in this area occurs at about −1 m relative to mean lower low water (MLLW). Desiccation (BOESE *et al.,* 2003), sediment movement, and wave action at this beach apparently restricts eelgrass distribution at depths more shallow than approximately −0.6 m MLLW. At depths greater than −1.0 m MLLW, eelgrass density declines. A 30-cm difference in depth can make a large difference in density at this site. Some plots, such as A and E, showed

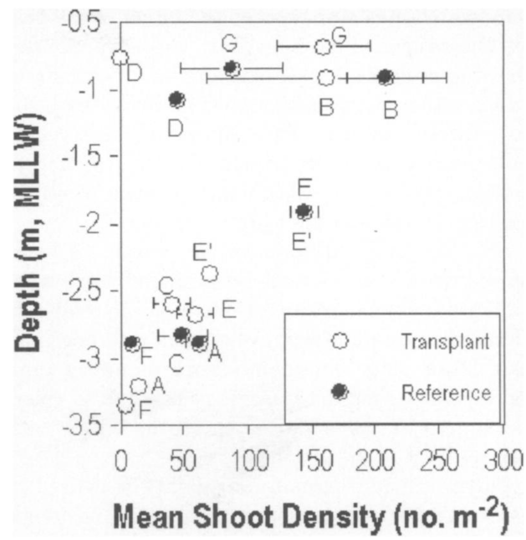

Figure 8. Eelgrass mean shoot density vs. plot depth (relative to mean lower low water, MLLW) at the Clinton Ferry Terminal in 2003. The 80% confidence limits are shown around the mean densities where they exceed the diameter of the point. Plot locations are shown in Figure 4.

large differences in depth as well as density between reference and transplant plots, whereas other reference-transplant plot pairs where depth is similar (e.g., plot B) showed high similarity in density. We concluded that because of the difficulty in locating appropriate reference sites in this area, the transplant plots and reference plots that should be compared are those that are positioned at the same depth, as opposed to those that are paired spatially.

Adaptive Recommendations

Six adaptations were made to the program at Clinton Ferry Terminal as a result of the information generated by the overall approach. First, total abundance was determined to be a better indicator of progress toward the goals than was mean shoot density. The project appears to be exceeding its goal of no net loss, but has not quite reached the performance criterion. The performance criterion is based on all plots combined. However, many of the plots are experimental with only a low or moderate probability of working (Table 4), and to include these in the evaluation may not be an accurate way to assess overall performance. There are more plants and a greater area of eelgrass now at the site than prior to construction, which meets or exceeds *the intent* of the goal for the project. Based on this, we recommended that the project be assessed relative to total abundance rather than density, to align better with the goal for the project. This allows for learning to take place with the experimental plots, which were not expected to do well but are proving useful in helping design and plan future projects.

Second, small differences in depth between paired transplant and reference plots, which were difficult to discern when establishing the reference plots, affected comparisons between reference and transplant plots. Therefore, performance of individual plots should be assessed relative to reference plots at the same depth, rather than with paired plots.

Third, regional climate variability appeared to have an effect on performance, as the reference plots showed a large increase in density over a period of 3–4 y. To expect new transplants to keep pace with a dramatically increasing natural population may be unrealistic, although the increasing trend suggests they are behaving similarly. Our recommendation was to make sure that natural variations such as these are factored into the assessment of performance by acknowledging that natural populations can respond more quickly to these types of variations than new and developing populations.

Fourth, using the information gained by the annual monitoring program, we recommended that some plots not be planted in 2003 because of very little chance of eelgrass survival (Table 4). Instead, we recommended that Plots B‴ and B⁗ (now labeled Plots I and J, respectively) be expanded in size because of the removal of a disturbance (a fishing dock) and the high success of nearby plot B. This was carried out in 2003 (Figure 4). Although quantitative monitoring was not yet carried out at the new plots I and J, where the fishing dock was removed, qualitative observations made in December 2003 showed that virtually all plantings had survived and shoots had increased substantially in length since summer 2003. With the impacts of shading and boating activity removed, and the relocation of the north ferry slip further offshore, this area appeared to offer near ideal conditions to support eelgrass meadow development.

Fifth, we are not sure how long monitoring should be carried out. The data suggest that deeper sites, which typically contain lower shoot densities due to lower light availability, stabilized within 5 y. In contrast, shallow, very dense sites showed substantial changes after 4–5 y. Shallow areas may more vulnerable to sediment erosion and deposition. Although climate variability was not studied, we speculate that it may have a greater effect on shallower, intertidal areas of the bed because of larger temperature variations as compared with deep, subtidal areas. Accordingly, they may be expected to exhibit a more dynamic equilibrium density compared with deeper sites.

Finally, working within an adaptive management framework may have institutional uncertainties. Because an adaptive approach, especially within a compensatory mitigation scenario, is somewhat new, we found that formalizing the decisions with the agencies was more difficult than expected. Two things that would have helped were not clearly defined: some kind of document to provide the formal vehicle acknowledging and approving the changes, and a schedule that would specify when this document should be finalized. Although this was considered a minor issue, it is worth clarifying in the planning stage of a project.

COMMON COMPONENTS OF EMERGING ADAPTIVE MANAGEMENT PROGRAMS

Based on our review of programs and projects, and our direct experience with projects, we conclude that is difficult to be highly prescriptive on the design of an adaptive management program for every coastal restoration scenario. The approach and level of detail varies greatly because of the differing nature of the programs. In addition, the level of documentation of the adaptive management scheme varies, primarily because it becomes the traditional way of doing business that does not require procedures to be written down. However, there are several common components emerging for programs and projects that are explicitly implementing adaptive management in coastal restoration. In our assessment, the most successful programs have dealt directly with uncertainties through systematic data collection, controlled manipulations, data analysis, and action-alternative selection based on an assessment of the data. Individuals involved in these programs understand the need to have information to make decisions in a systematic way, because funds are too limited for a simple trial-and-error approach, and people are committed to making their projects successful. The common components being used in successful coastal and estuarine restoration adaptive management programs include the following:

- Clear goal statement—drives what is done
- Conceptual model—organizes understanding
- Monitoring—provides information for management decisions
- Evaluation framework—provides mechanism to evaluate information openly and objectively
- Adjustment strategy—ensures clear plans and mechanisms to implement actions when adjustment is necessary
- Dissemination of information—lets others learn regionally and nationally.

STEPS TOWARD PREDICTABILITY

A principle aim in restoration is to be able to predict the outcome of restoration actions with increasing certainty (NRC, 1992). Adaptive management is the framework that is being used to increase predictability. We propose the following elements as keys to increasing predictability of coastal restoration projects:

- Admit that uncertainties exist, and address as many as possible in early pre-implementation phases; this is often difficult to carry out in compensation projects, but it is realistic and necessary.
- In projects where restoration is done as compensatory mitigation, consider overcompensation (relate amount to degree of uncertainty) for potential damages to account for uncertainties.
- Evaluate uncertainties through hypothesis-driven pre- and post-implementation experiments; keep the experiments as simple as possible.
- Develop predictive models, when appropriate, based on the data; this forces objectivity and transferability.
- Actively use performance monitoring information to adjust performance measures to align better with the intent of goals; re-examine the effectiveness and direct applicability of performance measures.
- Disseminate information for use in future projects; incorporate published papers and oral presentations at regional and/or national meetings as essential products of the project.

ACKNOWLEDGMENTS

This paper is based on a presentation at the Inaugural National Conference on Coastal and Estuarine Habitat Restoration, presented by Restore America's Estuaries, April 13–16, 2003, Baltimore, Maryland. We sincerely thank Mary Kentula and Gordon Thayer for organizing the session on "Coastal Restoration: Where have we been, where are we now, and where are we going." We thank several individuals for providing input to this paper: G. Steyer, R. Raynie, D. Fagergren, J. Dorhman, J. Muncy, and K. Hofseth. The original research project was co-led by Charles Simenstad of the University of Washington. We sincerely thank Professor Simenstad, along with other members of the University of Washington study team including J. Cordell, S. Wyllie-Echeverria, and A. Olsen for their contributions to this research. The research and restoration work has been sponsored since 1994 by Washington State Department of Transportation (WSDOT). We sincerely thank individuals associated with WSDOT, including J. Schafer, K. Forjour, R. East, J. Colby, and T. McKenzie of Anchor Environmental for their continued support. B. Williams of WDFW and R. Donnelly of NOAA Fisheries have been active participants in the annual meetings and adaptive management process. S. Thomas edited and E. Stoppani formatted the manuscript. M. Kentula, M. Miller, and two anonymous reviewers provided excellent comments.

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