

NEW UNDERSTANDING

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The Baylands and Climate Change



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A Summary of Findings from the Science Foundation Chapters
of the Baylands Goals Science Update

UPDATING OUR VISION FOR THE FUTURE

The Baylands¹ Ecosystem Habitat Goals Project (“Goals Project”), completed in 1999, spurred the restoration and enhancement of tens of thousands of acres of wetlands around the San Francisco Bay. This restoration enriched the Bay Area’s economy and its quality of life. It has provided cleaner water, flood protection, more wildlife, and beautiful places to be in nature in the heart of this urban region. The original Goals Project anticipated the need for updates to account for changes in scientific understanding, the environment, and social values. This report is the first “Science Update.” It advances the Goals Project by providing new science-based recommendations to address climate change and other key drivers, including sea-level rise, freshwater flows, and sediment supply, over the next century. This report describes actions that can be taken to ensure that the baylands continue to support the ecosystem functions and services that are vital to the ecological and economic health of the region. Its focus is on estuarine wetlands—namely, tidal flats and tidal marshes—because of the wealth of services they provide and the threat they face from rising sea levels and other aspects of future change.

This Science Update focuses on how to create resiliency in the baylands and their wildlife—the native plants and animals that use the baylands as habitat—so they can adapt to environmental change while retaining vital ecosystem functions. Planning for climate change creates opportunities to reenvision the baylands in the context of the estuary as a whole, including its watersheds, which are integrally connected environmental systems. When natural ecological processes are allowed to flourish across these systems, the baylands and their wildlife are inherently resilient. This natural resiliency can be enhanced, though this requires altering traditional approaches to shoreline management. Engineered shorelines do not adapt well to change; they are static and will require ever more intense and expensive solutions. Rather than

1. The baylands are all the areas upstream of the Golden Gate between minimum and maximum tide elevations, including the areas that would be flooded by the tides if not for levees or other unnatural water-control structures. This Science Update pertains only to the baylands downstream of Broad Slough, which demarcates the downstream limit of the Sacramento–San Joaquin Delta.



The future of the baylands will be defined by their ability to adapt to changing conditions.

see the baylands as fixed habitats, restoration managers need to take advantage of their ability to move and evolve by reestablishing and nurturing their natural formative processes, including nourishment by freshwater and sediment inputs from watersheds.

With significant changes in watershed and sediment management, marshes and mudflats could receive sufficient sediment and space to keep pace with, and adapt to, sea-level rise. Historical baylands that have been reclaimed for uses that are not compatible with climate change could be restored to the tides or otherwise repurposed. Ponds managed for wildlife could be reconfigured or moved. Space could be created within watersheds to accommodate the

inland migration of the baylands due to sea-level rise. In this vision, the vital ecosystem services of the baylands would be maintained. Achieving this vision will require accelerating the development and implementation of new restoration approaches, investing more resources, and adjusting public policies to ensure success. With help, the baylands can evolve and migrate, continuing to give the Bay Area ongoing flood protection, wildlife, clean water, carbon sequestration, and recreation opportunities for the next hundred years and beyond.

This summary chapter synthesizes information from six Science Foundation chapters, listed below and found at www.baylandsgoals.org, which provide significantly more detail on the most recent baylands science. The recommended actions that emerged from the Science Foundation chapters are presented in the following chapter: *New Opportunities: How We Can Achieve Healthy, Resilient Baylands*.

Purpose

This Science Update furthers the original purpose of the Goals Project to offer a long-term vision for a healthy and sustainable baylands ecosystem. Specifically, this report identifies key scientific findings that support recommended actions to sustain diverse and healthy communities of wild plants and animals in the baylands in the face of climate change and other stresses. The Science Update provides a scientific basis to guide regional planning for public and private interests seeking to maximize the ecological integrity of the baylands as part of a shore that is resilient to the impacts of climate change.

In keeping with the guiding principles of the Goals Project, the recommendations aim to

- ◆ achieve robust, functioning ecosystems with a preference for self-maintaining systems wherever possible
- ◆ prioritize the support of native species over nonnatives
- ◆ focus on biological communities more than individual species

As the estuary (defined in the geographic scope section below) continues to change over the next century, some of the species and biological communities that are present now are likely to change. Novel communities may arise, with nonnative species arriving via anthropogenic transportation and native species arriving via range shifts. Species will also be lost in the Bay Area due to extirpation or range shifts, and species that were present historically may not be able to survive. We therefore focus the recommended actions on preserving, protecting,² enhancing, and restoring the ecological functions of the baylands to sustain diverse and healthy wild plants and animals while recognizing that no one can control exactly how the ecosystem will be structured or which species will be present in each community.

This report focuses on the ecological integrity of the baylands, especially the tidal marshes and mudflats, yet acknowledges that the baylands provide many critical ecosystem services to the region. In particular, estuarine wetlands reduce flooding by attenuating waves and spreading out and slowing down high water, enhance water quality by filtering out and breaking down contaminants, provide nurseries for fish and shellfish, sequester carbon, and provide important recreational opportunities. Through these services, wetlands make valuable contributions to the local economy and quality of life and can be part of multi-objective, cost-effective, low-maintenance, nature-based solutions to protect developed infrastructure from sea-level rise and flooding.

Intended Use

This report is a guide for resource managers, planners, local governments, and other decision makers who are working to integrate the protection, restoration, and enhancement of thriving baylands ecosystems with infrastructure updates, watershed management, and plans for a future shore in the context of climate change.

Developed as a technical resource based on a synthesis of the best available science, this report is not a policy document. Rather than providing a comprehensive review of all baylands science, this report focuses on the actions that resource managers can take to maintain the ecological health of the baylands. The recommendations stem from the science and are intended to guide the planning, restoration, and management of the baylands; however, they must be reviewed, vetted, and adopted by individual agencies through formal public processes if they are to result in policy or regulatory changes. They likewise reflect the technical expertise of the contributors

2. Protect in the context of this report refers to land-use or land-tenure actions taken with willing partners and landowners to ensure the future availability of lands and waters to provide desired ecological benefits. Protection can be accomplished through management of lands acquired by fee, conservation easement, permit, lease, or cooperative agreement. Land protection may also be provided by local regulatory control through a formal public process, such as zoning, ordinance, or regulatory permit.

Box 1 The Success of the 1999 Baylands Goals

The 1999 Baylands Ecosystem Habitat Goals (Goals Project) galvanized the restoration of tidal habitats in the San Francisco Bay region. Prior to its publication, tidal wetland restoration projects were rare in the region and small in scale, with the largest around 350 acres. By providing a consensus-based scientific vision of the kinds, amounts, and distribution of baylands habitats needed to sustain healthy populations of fish and wildlife for the entire region, the Goals Project gave regulators, resource managers, environmentalists, and citizens the framework necessary to pursue large-scale restoration for baylands habitats.

In the decade after the Goals Project report was published, over 12,000 acres have been restored, and nearly 30,000 more are now under way. The report has become a cornerstone of policy, planning, coordination, and advocacy for the acquisition, protection, and restoration of the San Francisco baylands.

Policy and Strategic Planning

Many public agencies have incorporated the Goals Project into regional planning and policy documents. The San Francisco Bay Regional Water Quality Control Board referred to it as the nonregulatory component of a conceptual regional wetlands management plan. The San Francisco Bay Conservation and Development Commission amended its policies for tidal marshes and tidal flats, and for fish, wildlife, and other aquatic organisms in 2002, endorsing the Goals Project's recommendation to restore to tidal action 65,000 acres of land now diked from the bay. The California State Coastal Conservancy

2007 Strategic Plan referenced the Goals Project as the basis for the region's wetland restoration goals, and the San Francisco Bay Joint Venture incorporated the Goals Project's baylands habitat acreage goals (Habitat Goals) into its Implementation Plan, "Restoring the Estuary."

These actions have supported many restoration projects, including the Napa River Restoration Project, Cullinan Ranch, Sears Point, Bair Island, the South Bay Salt Pond Restoration Project, and many more throughout the San Francisco Bay region.



Salt marsh harvest mouse

to the report and do not necessarily reflect the positions of the agencies whose staffs participated.

Due to the nonregulatory and technical nature of the document, a formal public comment period was not undertaken; however, public engagement with the document is welcome. The document is intended as a resource in working with communities to develop regional and local strategies based on a wide range of criteria and concerns not fully addressed here, including economic constraints, landowner desires, land-use planning and regulation, and competing societal interests and priorities. It is hoped that the ecological visions, principles, and recommendations herein help inform those broader planning processes.

Public and Private Funding for Acquisition and Restoration

Funding for baylands restoration projects increased dramatically after the Goals Project was released. Environmental organizations such as Save the Bay, the Bay Institute, and the National Audubon Society successfully convinced a California State Senate Select Committee, US Senator Dianne Feinstein, and private foundations that the acquisition and restoration of the South Bay salt ponds was a keystone to implementing the Goals Project. In 2002, the Goals Project was specifically cited in the voter-approved Proposition 50, which included up to \$200 million for the Wildlife Conservation Board to implement projects recommended in the report. Over the past decade, this funding, along with other state bond funds, federal appropriations, and local and private funds, has enabled ecosystem-scale acquisition, planning, and restoration actions in the baylands.

Many smaller bay restoration projects have benefited from the Goals Project, as state and federal agencies increasingly rely on credible science-based plans to identify acquisition and restoration projects that meet their habitat- and water-quality grant-program mandates.

Federal and State Legislation to Create a Regional Funding Source

The Goals Project recommendation to reestablish 100,000 acres of tidal wetlands in the bay has been the driving force in securing new funding sources. In 2008, Save the Bay successfully sponsored legislation (AB 2954, Lieber) that created the San Francisco Bay Restoration Authority, which has the capability

to raise and grant regional funds to restore bay wetlands.

The Goals Project has also spurred regional entities in working with US Representative Jackie Speier and Senator Dianne Feinstein to seek a federal funding program (the San Francisco Bay Improvement Act of 2010) comparable to other nationally significant bay-restoration programs to accelerate the restoration of the bay.

Development of Regional Goals for Other Habitat Types

The Goals Project inspired the development of two other regional science-based habitat conservation visions:

- ▶ The Bay Area Open Space Council developed the Conservation Lands Network, which identifies the types, amounts, and distribution of habitats needed to sustain diverse and healthy ecosystems in upland habitats beyond the baylands. The report, the culmination of five years of work by 125 experts, serves as a guide for making conservation investments, supporting collaborative conservation planning, and helping to protect biodiversity throughout the region.
- ▶ The San Francisco Bay Subtidal Habitat Goals Project, produced by a collaboration of public agencies and a panel of scientists, marks the first time that comprehensive information about submerged areas in the bay has been compiled. It includes broad regional goals for protecting and restoring underwater habitats in the bay, with detailed objectives and actions for implementation over a 50-year planning horizon.

Thus, instead of a set prescription, this report outlines a broad suite of actions for evaluation that are intended to be implemented voluntarily, incrementally, and cautiously in the coming decades. These actions can be adapted to create regional and site-specific solutions that match the particular context and needs of communities involved.

Additionally, the report is neither an environmental impact statement nor an environmental impact report intended to meet requirements of the National Environmental Policy Act or the California Environmental Quality Act. Any project that proposes to implement recommendations within this document will need to undergo appropriate environmental impact analysis.

RELATIONSHIP TO THE 1999 BAYLANDS ECOSYSTEM HABITAT GOALS

The Goals Project developed the first comprehensive vision of how to restore the baylands ecosystem. Goals were set in the form of habitat-acreage³ targets, general landscape configurations, and habitat elements (the “Habitat Goals”). Notably, the regional acreage goals called for tidal marsh restoration on an unprecedented scale: 60,000 acres to be restored, to reach a total of 100,000 acres. These acreage targets remain principal goals and are not revised here. This Science Update uses new scientific knowledge to revise the recommendations found in chapter 5 of the original Goals Project report and provides new recommendations to achieve the original acreage goals.

Impact of the 1999 Goals Project

The Goals Project galvanized the restoration of tidal habitats in the San Francisco Bay region. Prior to its publication, tidal wetland restoration projects were uncommon, small in scale, and mostly planned in isolation from each other and from surrounding landscapes. The Goals Project provided environmental policy makers, regulators, resource managers, and nongovernmental advocacy organizations with a scientifically based consensus vision of the kinds, amounts, and distribution of baylands habitats needed to sustain healthy populations of fish and wildlife for the entire region. The Goals Project gave birth to new, more collaborative ways to approach ecological planning across policies and programs at all levels of government.

The Goals Project has become a cornerstone of policy, planning, coordination, and advocacy for the acquisition, protection, enhancement, and restoration of the baylands. Between the Goals Project in 1999 and the latest comprehensive baylands habitat mapping in 2009, 9,000 acres of diked baylands were restored

to tidal baylands and 2,000 acres of diked baylands were created or enhanced for wildlife support. In addition, 23,000 more acres are being planned for restoration to tidal baylands, and another 8,000 acres of diked baylands will be created or enhanced for wildlife support (see box 2 for more details). The Goals Project has been incorporated into many public-agency planning and policy documents and has brought significant focus and resources to the implementation of its habitat goals. This success inspired the development of science-based habitat-conservation visions for Bay Area watersheds (*Conservation Lands Network*) and subtidal habitats (*San Francisco Bay Subtidal Habitat Goals Report*).

Migrating terns arrive at a restored wetland.



3. Because the habitat goals were set in acres, this report contains both the metric units typical of standard scientific practice and the nonmetric unit of acres when referring to habitat areas.

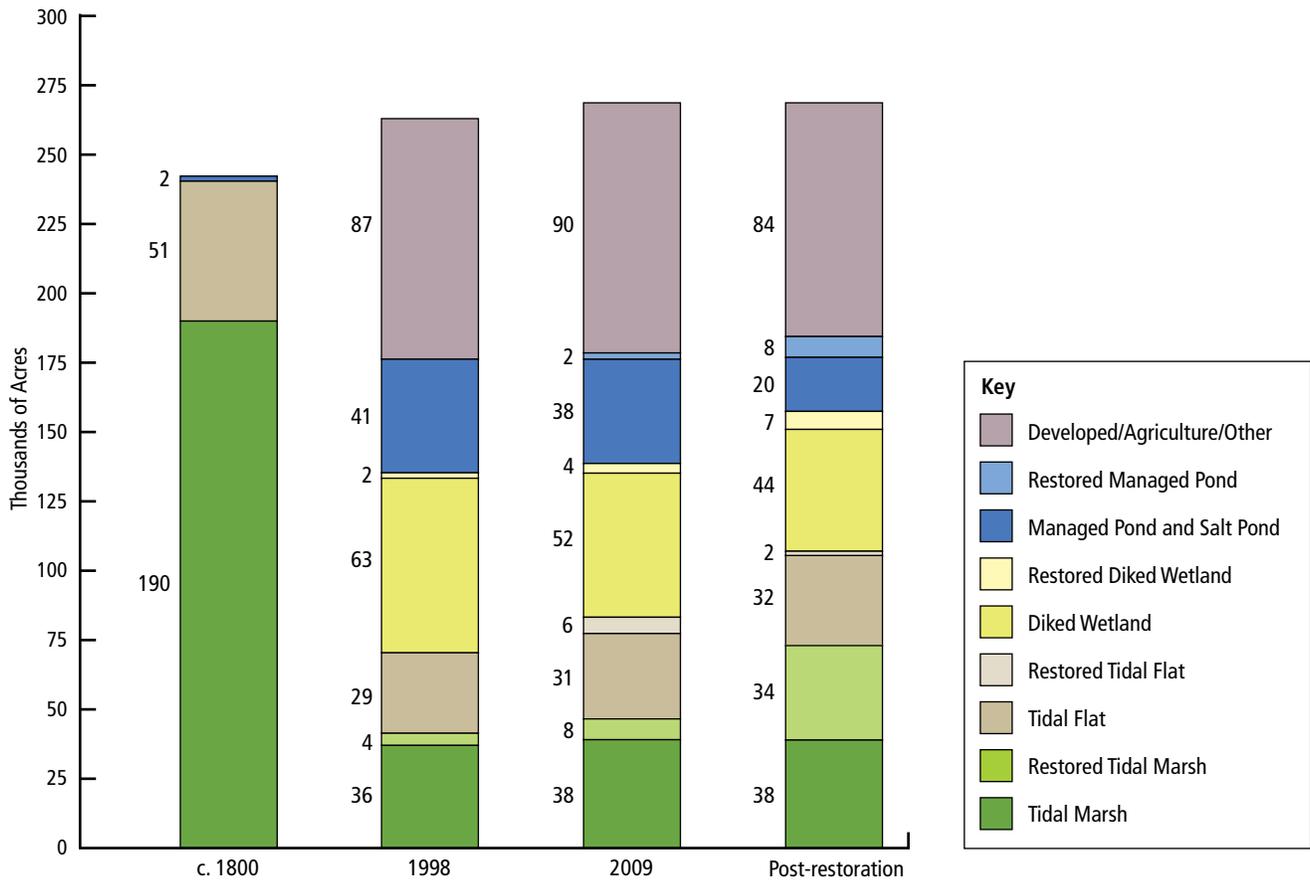


Figure 1 Change in the extent of baylands habitats over time. Numbers on bars represent thousands of acres. Acres of restored habitat in each time period are cumulative for each habitat type (e.g., restored tidal marsh in 2009 reflects all marsh restored before 2009, including marsh restored prior to 1998). To standardize the habitat types among different mapping efforts, some calculations are slightly different here from those in the 1999 Goals Project (see box 2 for more details).

Restoration managers are now poised to implement the broader concepts underlying regional restoration and to design complex multicomponent systems that incorporate dynamic processes and natural ecological variability. By doing so they will help establish resilient baylands ecosystems that can adapt over time, support native wildlife, and provide the ecosystem services upon which the region relies.

Process for Developing the Science Update

The success of the Goals Project motivated the authors of this update to follow a similar process and organizational structure. The key organizational elements were (1) a steering committee of representatives from resource management and science organizations, (2) collaborative and open participation by science contributors organized into workgroups, (3) an independent science review panel, and (4) a core administrative team, including the science coordinator.



Wetlands at sunset

Well over 100 scientists and managers contributed to the Science Foundation chapters. The chapters, each developed by a workgroup led by two co-chairs, are described below:

- ◆ **Science Foundation Chapter 1: The Dynamic Workings of the Baylands** lays out conceptual models of how drivers of change influence the evolution of baylands habitats.
- ◆ **Science Foundation Chapter 2: Projected Evolution of Baylands Habitats** details what is known about how the geomorphology of the baylands is projected to evolve under the future scenarios.
- ◆ **Science Foundation Chapter 3: Connections to the Bay** covers how changes in the bay, delta, and ocean may affect the baylands. Several case studies that furnish examples of the vulnerabilities and potential responses of key wildlife species and groups are provided.
- ◆ **Science Foundation Chapter 4: Connections to the Watersheds—The Estuarine–Terrestrial Transition Zone** describes the important area where the baylands transition to their watersheds, including information on transition zone types and ecosystem services.
- ◆ **Science Foundation Chapter 5: Risks from Future Change for Wildlife** focuses on how wildlife populations and communities may be harmed by future changes. The chapter includes several case studies that furnish examples of the vulnerabilities and potential responses of key wildlife species and groups.
- ◆ **Science Foundation Chapter 6: Carbon Sequestration and Greenhouse Gases in the Baylands** discusses carbon storage in the baylands as well as greenhouse gas emissions.

Standardization of processes and products was accomplished in several ways. First, the science contributors developed a conceptual model of the physical, chemical, and biological processes that govern the formation of baylands and the evolution of habitat types. The Dynamic Workings of the Baylands below (and Science Foundation chapter 1) summarizes this model. Other models developed by the workgroups for subsequent Science Foundation chapters link to the overarching landscape model. Second, we developed several scenarios of future change to guide the analyses of each workgroup. Finally, scientific discussions, revisions of these documents, and coordination of feedback on the many drafts were made possible by extensive communication among workgroup chairs and the science coordinator.

The content of this report reflects the guiding principles that emerged from the authors' discussions with the steering committee and workgroup chairs. Of particular importance was the use of the best available science. The guiding principles, organizational structure, timing, and funding of the effort are described in greater detail in appendix A.

The report went through several rounds of review by the science contributors, workgroup chairs, science review panel, and the steering committee. A near-final draft of the report was sent for review to more than 50 individuals, representing a range of baylands stakeholders. After each round of review, content was revised to address the feedback received.

Much of the effort contributed to the Science Update was provided in kind by the participating organizations and individuals. Major funding was provided by the California State Coastal Conservancy, the Gordon and Betty Moore Foundation, and steering committee organizations, with additional assistance from the California Landscape Conservation Cooperative and the San Francisco Bay Wildlife Society.

Geographic Scope

This report mirrors the geographic scope and subregional breakdown of the Goals Project. It includes the portion of the San Francisco Bay–delta estuary downstream of the Sacramento–San Joaquin Delta, with the demarcation at Broad Slough (fig. 2). Within this area, the Goals Project designated four subregions: Suisun, North Bay, Central Bay, and South Bay. The baylands were further divided into 20 segments to allow a more detailed examination of restoration needs and opportunities.

Within this geographic area, the Science Update focuses on the baylands and the greater baylands ecosystem (fig. 2). The baylands are

Marsh channels and vegetation in Salt Pond A21





Figure 2 Goals Project area



defined as the lands that lie between the maximum and minimum elevations of the tides over multiyear cycles, including those areas that would be covered by the tides in the absence of levees or other unnatural structures. The baylands ecosystem, as defined by the Goals Project, includes the baylands and their adjacent waters and lands, and their associated communities of plants and animals.

To the east of the baylands lies the Sacramento–San Joaquin Delta, which is part of the estuary and has important physical, chemical, and biological interactions with the bay. While addressing the delta in detail is beyond the scope of the Science Update, the important physical, chemical, and biological connections between these two parts of a single estuary are acknowledged. Major changes in the delta that could affect the bay, and vice versa, are noted.

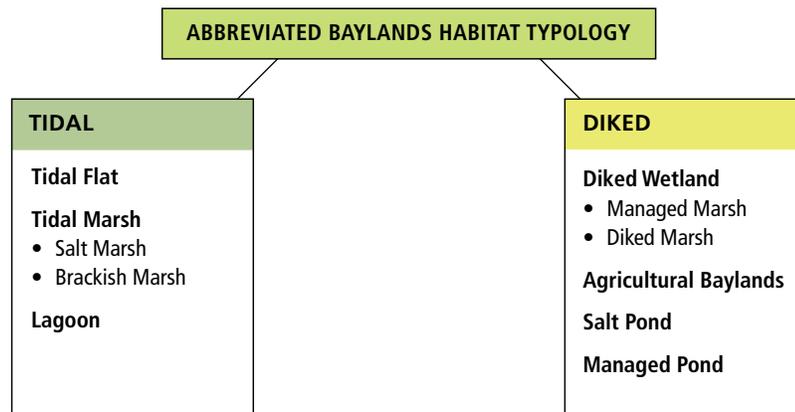
Baylands Ecosystem

The baylands lie between the San Francisco Bay and its watersheds and rely on the energy and materials provided by these adjacent ecosystems. Tidal, fluvial, and terrestrial processes are critical to the baylands' formation and maintenance even when originating outside them. Thus, restoring resilient baylands requires looking outside as well as inside their boundaries. Moreover, within the baylands, processes and functions in one part of the ecosystem affect outcomes in other parts. The geographic relationships between the habitat types and their connections by physical, chemical, and biological processes greatly affect their functioning.

Changes imposed by the urbanization of the baylands and their watersheds have fragmented baylands habitats and disconnected or otherwise modified the processes that drive ecosystem functions. As we consider how to protect the ecological integrity of the baylands over the next century, restoring hydrologic and geomorphic processes that sustain the landforms will be critical. As a co-benefit, using natural processes to maintain ecosystems can be a low-cost, low-maintenance approach to retaining the services the baylands provide, which include flood protection, water-quality improvement, and recreational opportunities. Thus, the Science Update recommends the restoration of complete tidal wetland systems and the processes that sustain them (see chapter 2: New Opportunities).

The baylands include tidal and diked habitats (fig. 3). Tidal baylands are subject to the daily action of tides. Diked baylands are areas of historical tidal habitats that have been isolated from tidal action by the construction of levees, tide gates, or other water-control structures. The most prevalent types of tidal baylands are tidal marsh

Figure 3 Major habitat types



and tidal flat (mainly mudflat). The most prevalent types of diked baylands are managed marsh (mainly duck clubs and wastewater treatment marshes), agricultural baylands, salt ponds, and managed ponds. Most of the acreage of managed ponds in the baylands is managed to enhance the habitat value for wildlife. This category includes wastewater treatment ponds and impounded waters in urban and residential areas (e.g., Lake Merritt and Bel Marin Keys). Here we will refer to *managed ponds* as those diked baylands that are physically separated from the tides by a berm or levee and have artificially controlled water levels or salinities through a weir, culvert, or flap gate. The baylands ecosystem and habitat types are described in detail in the 1999 Goals Project (see chapters 2 and 4 of that report). The habitat typology has been slightly modified for the Science Update to include managed ponds.

CHANGE IN BAYLANDS HABITATS OVER TIME

Progress toward the Habitat-Acreage Goals

Between 1800 and 1998, 79 percent of tidal marshes (150,000 acres) and 42 percent of tidal flats (21,000 acres) were lost to diking and filling (figs. 4–6).⁴ In the late 1980s through the 1990s, habitat loss was slowed and then reversed through the protection of threatened parcels and early restoration activities. The Goals Project provided the first comprehensive measurement of baylands habitat extents, and estuarywide mapping was repeated using aerial imagery from 2009 as part of the development of EcoAtlas.

For this Science Update, existing information about planned and ongoing restoration projects was assembled primarily from the Wetland Project Tracker and the San Francisco Bay Joint Venture. Contributors to the Science Update reviewed the data and provided best estimates of expected habitat outcomes for particular sites.

Restoration projects completed by the year 1998 added 4,000 acres of tidal marsh and 2,000 acres of diked wetlands (figs. 5 and 6). If currently planned projects are successful, they will add around 28,000 acres of tidal marsh—including 5,000 acres of

⁴ These numbers differ slightly from those reported by the Goals Project due to mapping differences.



Pickleweed marsh

previously restored tidal flat that will evolve naturally into tidal marsh (fig. 7)—to the baylands habitats mapped in 2009. Although 54,000 acres of managed ponds are planned for restoration or enhancement, the overall extent of managed ponds will be reduced by 13,000 acres. Similarly, 35,000 acres of diked wetlands will be created or enhanced, but the overall diked wetland extent will decrease by 3,000 acres. This estimation of future baylands extent (fig. 7) includes restoration, enhancement, and mitigation projects that have been funded, permitted, or both and

therefore have a high probability of completion within the next 20 to 30 years. See box 2 and appendix B for a detailed discussion of assumptions and data sets.

In summary, of the 60,000 acres of tidal marsh recommended for restoration by the 1999 Goals Project, over 7,000 acres of tidal marsh were restored as of 2009, and 28,000 more acres of restored tidal marsh are expected to result from future projects or habitat evolution of current projects. In addition, today's baylands include mudflats,

Box 2 Mapping the Changing Baylands: Methods and Assumptions for the Baylands Habitat Maps

Habitat maps in this report use data from the 1997 Bay Area EcoAtlas, the 2009 Bay Area Resource Inventory (BAARI), and the Wetland Project Tracker. EcoAtlas 1997 represents the most up-to-date baylands habitat-type data layer available at the time of the 1999 report publication. BAARI 2009 represents the most complete regionwide baylands habitat-type data layer currently available. It includes detailed information on all tidal and nontidal aquatic features in the region. Information on the mapping procedures and standards used are available at <http://sfei.org/baari>. The BAARI layer was released in 2009, but the date of the imagery used for some areas could be earlier. Wetland Project Tracker data were used to determine the status and extent of restoration or mitigation projects during each time period. Projects represented were issued a Clean Water Act Section 401 Certification and/or Waste Discharge Order from the Regional Water Quality Control Board. Additional information about wetland projects was provided by local land managers and agencies.

The 1998 and 2009 maps show projects where groundwork has been completed. The future habitat map includes projects in progress and planned projects that have been funded, permitted, or both. They therefore have a high probability of completion within the next 20 to 30 years. For the future habitat

map the predominant habitat type was mapped across the full extent of each identified project area or subarea, and the maximum tidal marsh extent was assumed for projects with multiple future scenarios. Therefore, future tidal marsh extent is likely overestimated. The future habitat map does not include the projected evolution of habitats due to climate change and sea-level rise. It should be noted that much of the difference in non-restored tidal marsh, non-restored tidal flat, and urban/agriculture acreage between 1998 and 2009 is due to differences in mapping and available data layers between the two time periods.

These maps are meant to provide an overview of bayland habitat extents, and details may be incorrect or inconsistent between maps due to incomplete information in the data layers used or inconsistencies in the habitat-type definitions used for different data sets. They are not adequate for jurisdictional or regulatory purposes. Note that the 2009 map shows a greater level of detail due to the improved tools and data layers available. Given the need to create equivalent habitat-type categories among the different mapping efforts, some calculations are slightly different here than in the 1999 Goals Report. See appendices B and C for more detail on mapping methods and assumptions.

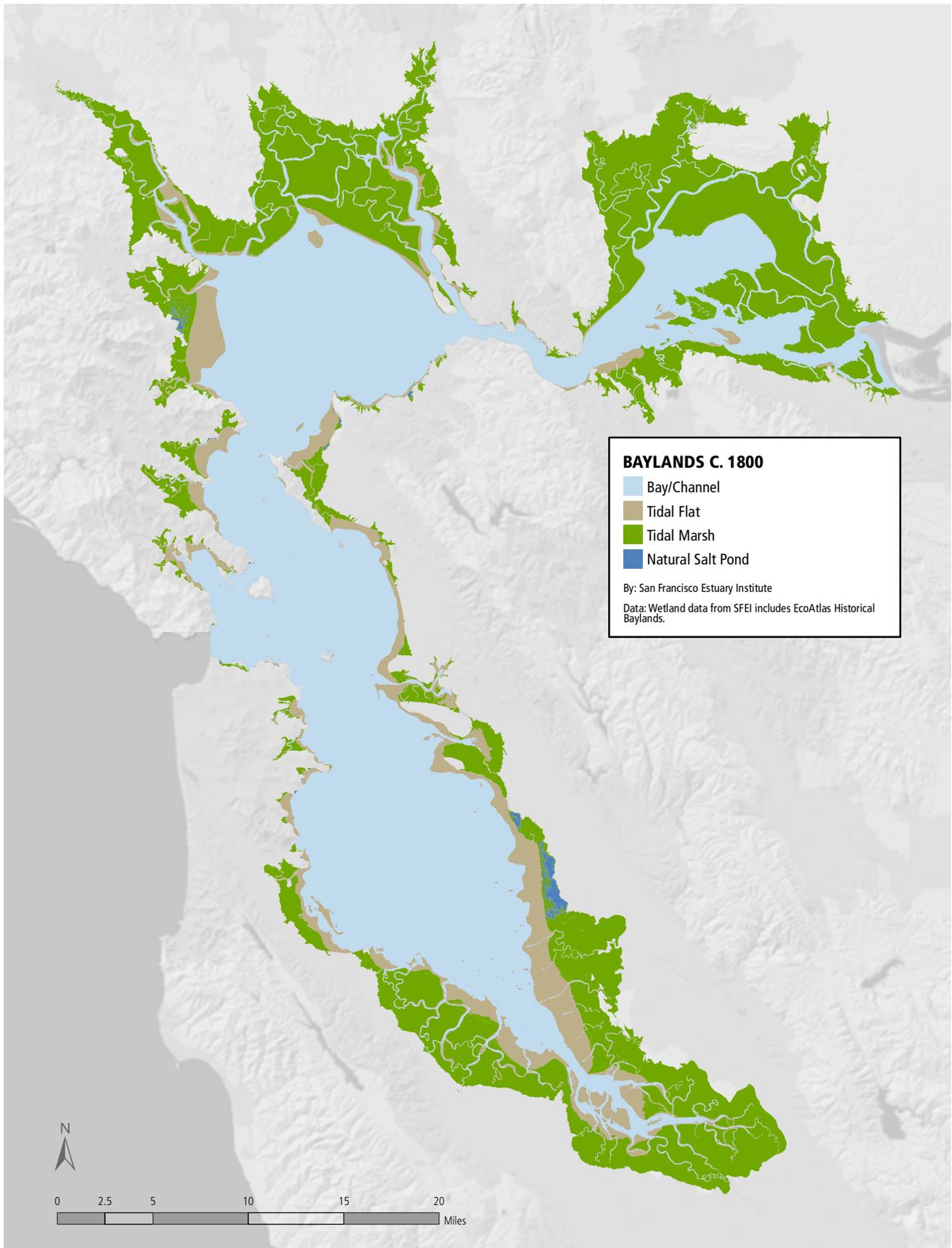


Figure 4 Baylands habitats c. 1800. See box 2 for more detail about the data and assumptions for this map.

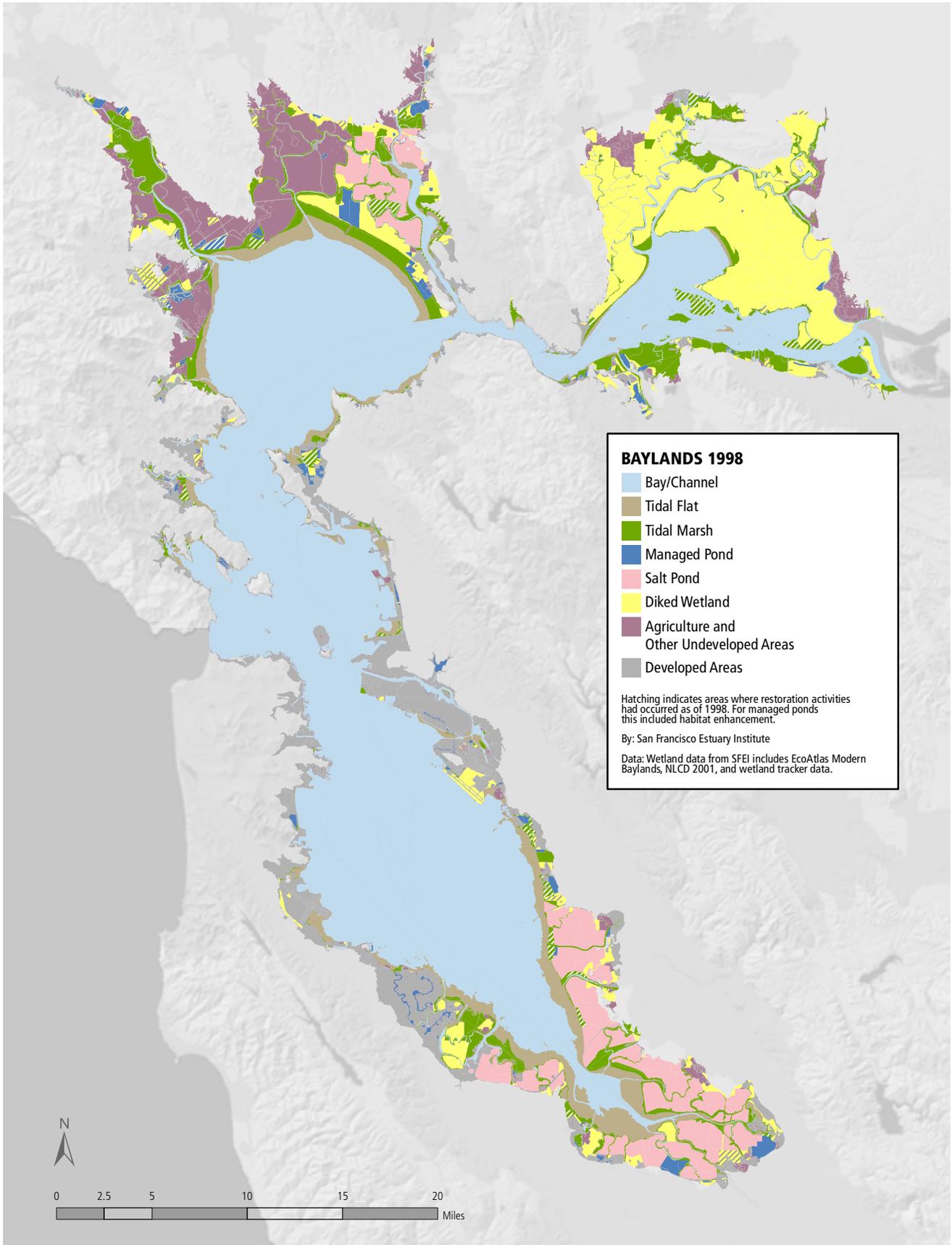


Figure 5 Baylands habitats in 1998. See box 2 for more detail about the data and assumptions for this map.

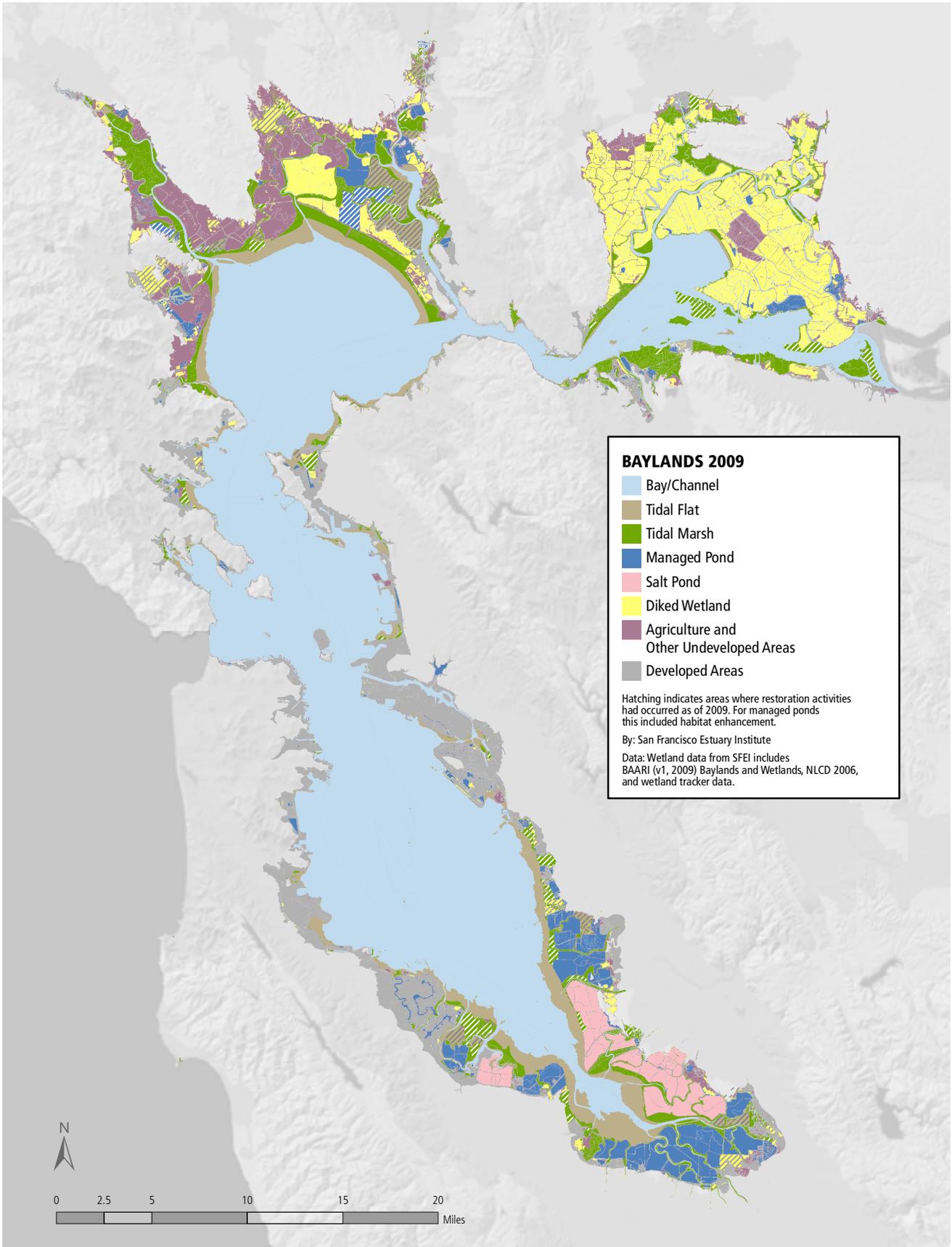


Figure 6 Baylands habitats in 2009. See box 2 for more detail about the data and assumptions for this map.

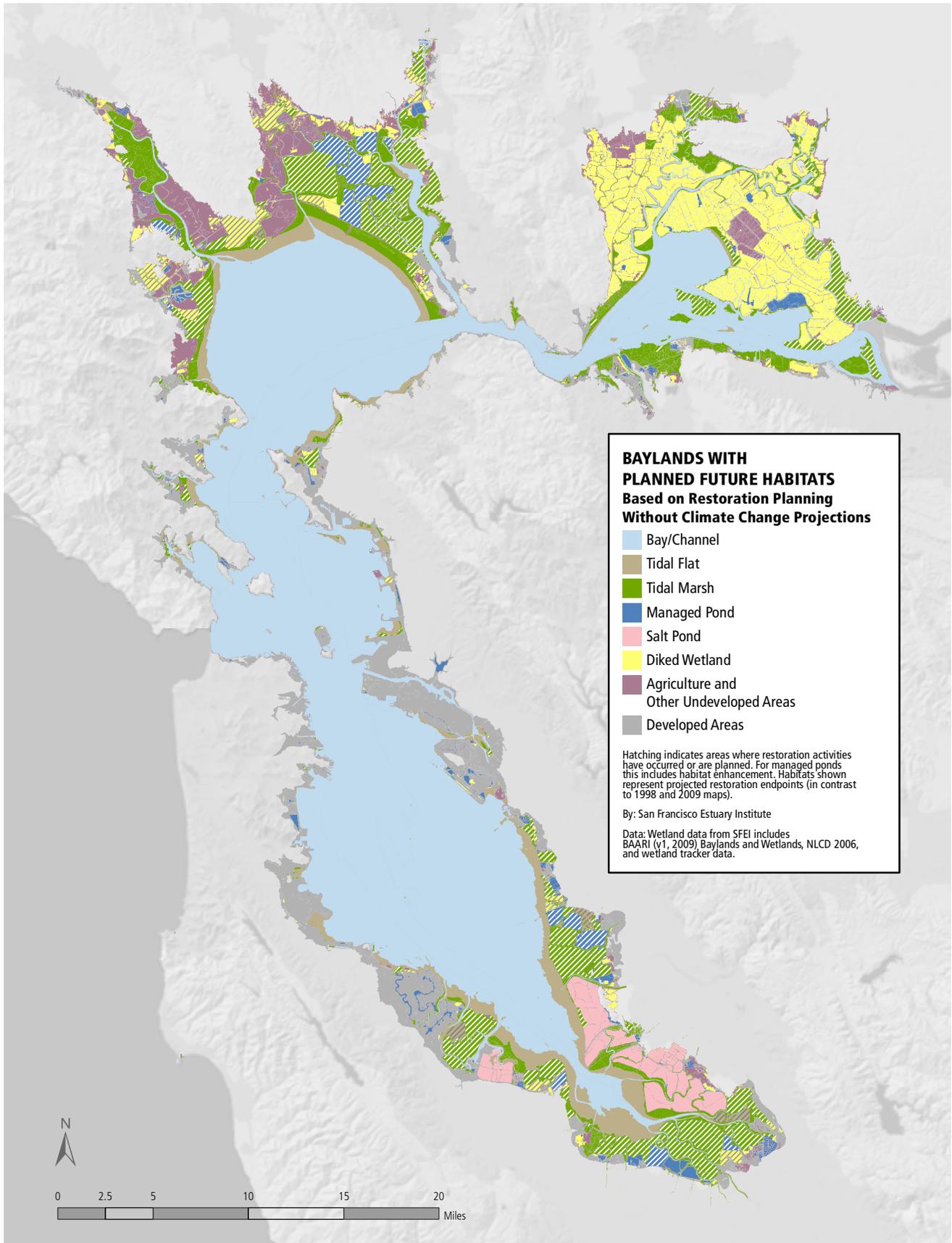


Figure 7 Baylands habitats with planned projects. See box 2 for more detail about the data and assumptions for this map.



Coyote Hills Regional
Park

diked wetlands and ponds, and other habitat types that provide critical support for wildlife.

Looking forward (fig. 7), the largest expanse of undeveloped baylands that are not already slated for particular restoration projects is in Suisun. Suisun has tens of thousands of acres of diked wetlands that are managed principally for duck hunting. Restoration plans for Suisun will need to be coordinated between the San Francisco Bay and delta regions, given the overlapping authorities of the Bay Conservation and Development Commission, the Delta Stewardship Council, and their respective planning documents. The Suisun Marsh Management and Restoration Plan is a key guiding document for Suisun Marsh.

The other three subregions also provide opportunities for reaching the habitat-acreage goals. In the North Bay, much future restoration is already planned, but some large agricultural areas in the northwest area of the subregion could be considered for restoration. Less opportunity exists in the Central Bay, where the baylands are constrained by steeper slopes and extensive urbanization, so smaller projects will be the focus there. In the South Bay, remaining commercial salt ponds totaling several thousand acres could, if made available for restoration, link the Alviso and Eden Landing portions of the South Bay Salt Pond Restoration Project. In order to better visualize potential restoration opportunities, the maps depict the distribution of agriculture as well as low- to medium-density and high-density development.

Changes in Habitat Configuration

While the Goals Project quantified the loss of baylands habitat extent, it could only describe the loss of habitat quality. As changes in climate and other ecosystem and land-use drivers challenge managers' ability to maintain extensive baylands acreage, the quality of the habitats becomes ever more important. Here we describe an analysis of marsh fragmentation.

The configuration of baylands habitats has changed dramatically since 1800. Tidal marshes have become more fragmented, with much more edge relative to interior or core areas and some isolated habitat patches. These changes in habitat configuration are common in modern landscapes and are likely to reduce some support functions for resident marsh wildlife above and beyond the loss in habitat extent. Against a background of severe habitat loss, fragmentation has reduced the baylands' ability to support wildlife by decreasing the connectivity between populations and increasing edge effects that promote predation and anthropogenic stress.

FRAGMENTATION OF TIDAL MARSHES

Due to extensive fragmentation of once-large, nearly continuous marshes, the average size of tidal marsh habitat patches has declined since 1800 (figs. 4, 5, and 8). Large marsh patches in the current baylands are primarily composed of wide marsh areas connected by narrow fringing marsh. The complex shape of these patches leads to a high proportion of edge habitat, where predation and other stressors are intensified (fig. 9). For this

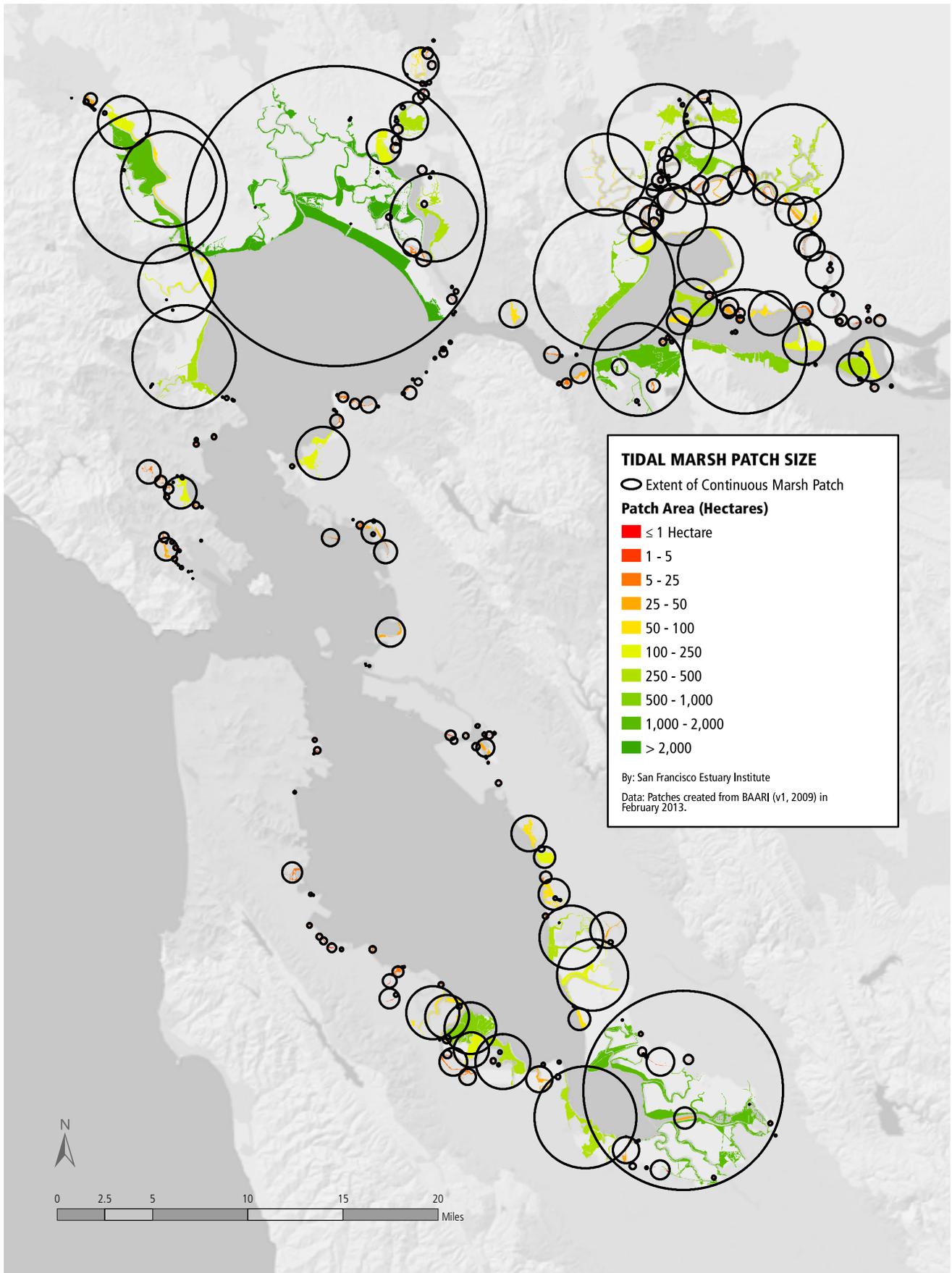


Figure 8 Tidal marsh patches by size in 2009. Each circle encompasses a patch.

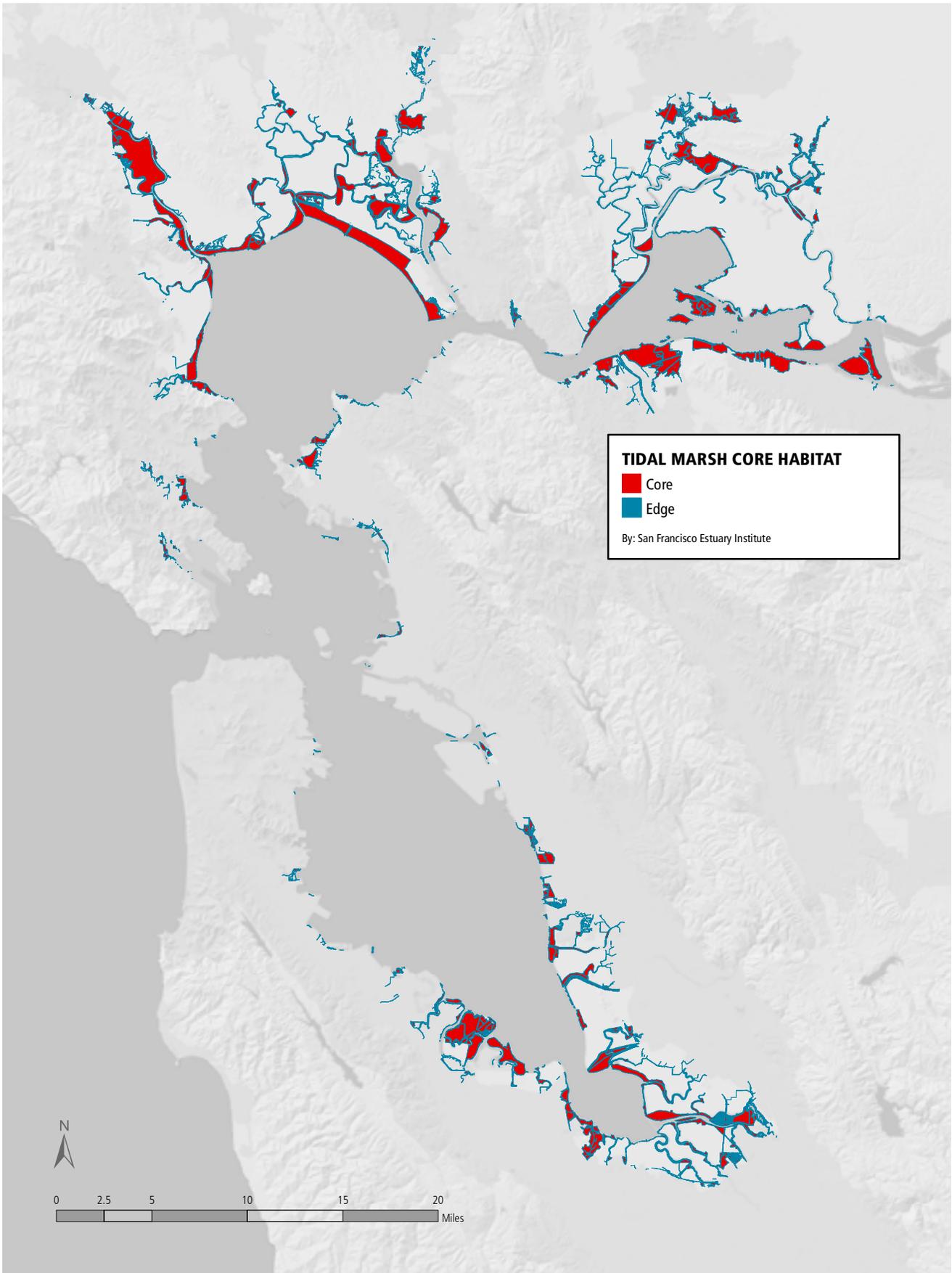


Figure 9 Core and edge tidal marsh habitat in 2009

analysis, *edge habitat* is defined as within 50 meters (164 feet) of the marsh edge, and the rest of the marsh interior is defined as *core habitat*. Also, habitat patches are considered separate if they are greater than 60 meters (197 feet) apart. For the justification behind these definitions, and for other details of this analysis, see appendix C.

Marsh fragmentation varies across the region (fig. 10). The Central Bay has the fewest, smallest, and most isolated marshes. The North Bay has the largest average marsh patch size (205 acres) and the largest marsh patch in the bay (8,518 acres; fig. 9). The South Bay has the second-biggest patch (4,655 acres) and second-largest

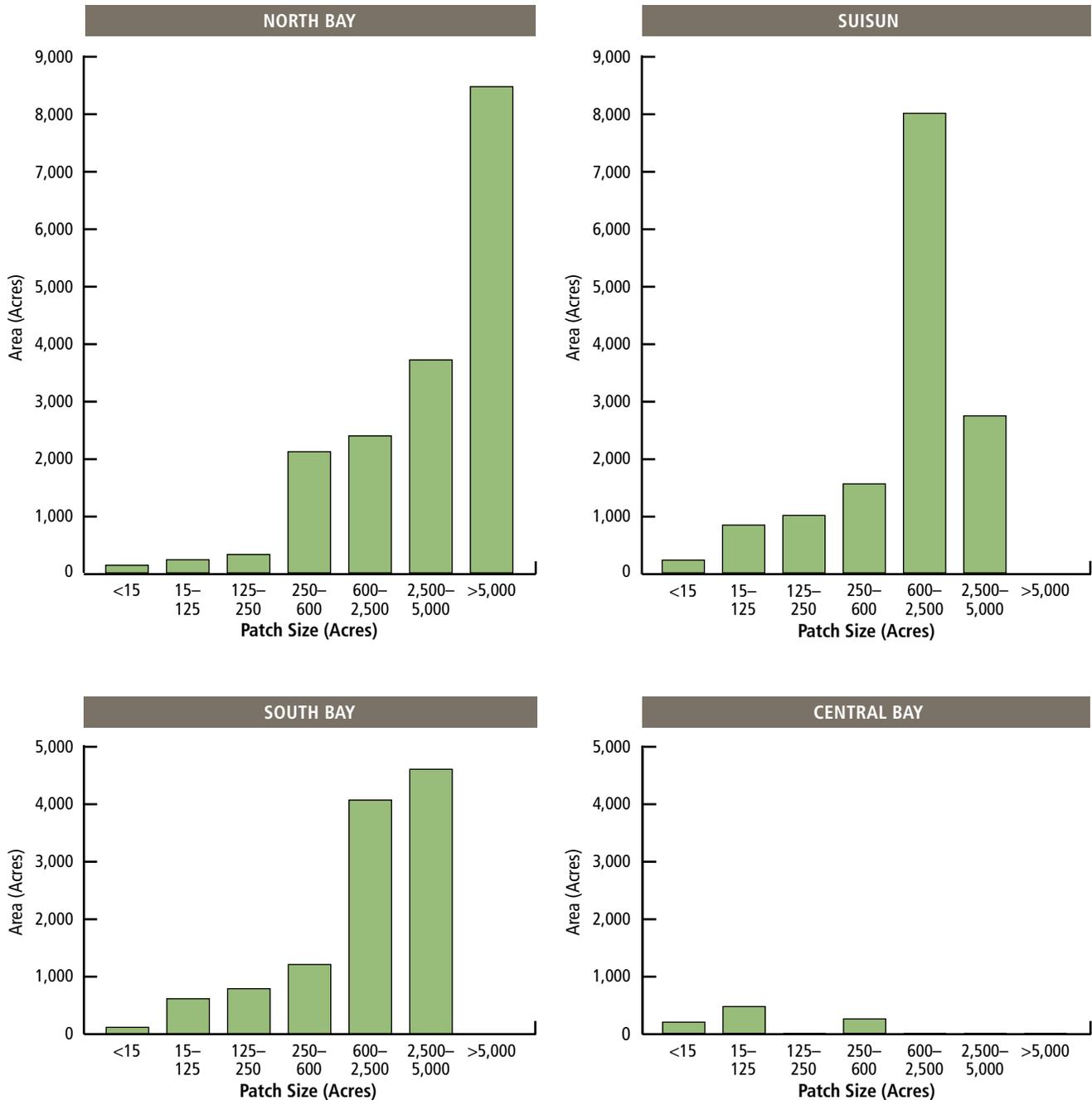


Figure 10 Total marsh area within each patch-size category for each subregion in 2009



Size, shape, and connectivity of patches are key to their habitat function.

average patch size (172 acres). The South Bay has a greater proportion of edge to core marsh habitat than either the North Bay or Suisun. The discontinuous fringing marsh in Suisun may account for the smaller average size of marsh patches in that subregion. While the tidal sloughs in North and South Bay appear to have filled in during the past 200 years, creating miles of fringing marsh, the channels in Suisun have not, for the most part.

Framing Future Change in the Baylands

Despite recent advances toward meeting the Habitat Goals, the extent of historical losses and the current level of fragmentation across the estuary remain significant vulnerabilities for the baylands' ecological functioning. At the same time there are new threats to the baylands from accelerating climate change. The climate will continue to warm, heat waves will increase in intensity and duration, sea levels will rise at least a few feet, and extreme storms and droughts are projected to become more frequent. Sea levels are projected to increase rapidly in the middle decades of this century, with the National Research Council projecting a regional sea-level rise for San Francisco Bay of 12 to 61 centimeters (about 4.5 to 24 inches)

by 2050 and 42 to 166 centimeters (about 16.5 to 65 inches) by 2100. The long-term increase will include periods of both slower and more rapid change, driven by oceanic processes such as El Niño and the Pacific Decadal Oscillation (PDO). In particular, the cold phase of the PDO currently suppresses sea level. Sea levels will be enhanced when the PDO shifts to a warm phase (or when a strong El Niño occurs), exacerbating impacts on the baylands associated with higher seas.

Additionally, less precipitation will be stored as snow into the summer months, resulting in runoff that is higher in winter and lower in summer. These changes in precipitation may affect water-management practices and, consequently, a large portion of the freshwater inflows into the bay. These changes will not always be slow and steady; rather, a greater number of severe episodic events are projected to produce significant changes in the landscape on a short timescale.

The baylands are particularly vulnerable to the anticipated increase in sea-level rise, reductions in sediment availability, the stressors and limitations imposed by urbanization around the baylands, and other aspects of expected change (see *The Dynamic Workings of the Baylands*). Ultimately, the concern is that marshes and mudflats will drown, leaving only narrow, fragmented habitat patches along the shoreline. Such patches would be squeezed up against levees and seawalls with development behind them, exacerbating flooding and creating deleterious edge effects within the baylands. These impacts would be additive or synergistic with other stressors that may also increase, such as invasive species, contaminants, and reductions in freshwater inputs.

Future Scenarios Evaluated

Particular scenarios of change were evaluated as part of the Science Update. These scenarios represent the most current projections published in the peer-reviewed scientific literature. The scenarios were built around climate-change and marsh-accretion models, emissions scenarios, and sediment supply. The uncertainty inherent to these future projections was addressed by selecting scenarios that bracketed the low and high ends of key drivers. All workgroups assessed the same scenarios using a standardized approach. The scenarios were based on (1) the newest estimates for sea-level rise for the California coast from the National Research Council, (2) the Marsh98 accretion model applied across the full Goals Project area, and (3) two climate-change scenarios from the US Geological Survey Computational Assessments of Scenarios of Change for the Delta Ecosystem (CASCaDE) project, downscaled for this region, that were selected to roughly bookend a range of possible climate outcomes for the bay–delta ecosystem. The CASCaDE projections included extreme weather events.

To develop the scenarios, the Science Update first examined the results of the CASCaDE modeling, which project that the San Francisco Estuary will have

- ◆ an increase in air temperature
- ◆ an increase in the salt content of water
- ◆ a possible decline in precipitation (with little chance of an increase) and runoff, and a very likely decline in snowmelt contribution to runoff
- ◆ earlier runoff, as precipitation is not stored in snowpack for as long
- ◆ possibly lower suspended-sediment concentrations (very unlikely to increase)
- ◆ an increase in the frequency of extreme environmental conditions, such as higher water temperatures, higher storm surges, higher flood peaks, and possible droughts

Given these results, the workgroups considered five scenarios for conditions in the year 2110:

- ◆ Scenario 1—low sea-level rise (52 cm, 1.7 ft), low sediment
- ◆ Scenario 2—low sea-level rise (52 cm, 1.7 ft), high sediment
- ◆ Scenario 3—high sea-level rise (165 cm, 5.4 ft), low sediment
- ◆ Scenario 4—high sea-level rise (165 cm, 5.4 ft), high sediment
- ◆ Scenario 5—severe storm event

The workgroups evaluating scenarios 1 through 4 were asked to consider projected changes in tidal marsh under different sediment and sea-level rise conditions and the range of other climate-change factors bookended by the two CASCaDE scenarios.

Scenario 5 was a projected storm event taken from the long-term CASCaDE projections. The storm resembles the flood of 1986, consisting of back-to-back atmospheric river events. This scenario calls for a large storm with heavy precipitation

coinciding with a high tide. It is representative of water levels that will become more frequent over time as sea levels rise.

For more details about these scenarios, see appendix D.

THE DYNAMIC WORKINGS OF THE BAYLANDS

The likely effects of the scenarios described above on the baylands and their wildlife will be mediated by the processes and drivers that form, maintain, and influence the ecological functioning of the baylands. The following discussion summarizes our current understanding of these processes and drivers, building on detailed information found in Science Foundation chapter 1. The restoration approaches presented in this report are based on these processes.

Natural Processes Conferring Resilience on the Baylands

The San Francisco Bay's evolution during the historical and late Holocene periods suggests a strong potential for resilience to climatic variation and helps identify the challenges and opportunities for human intervention that could enhance this adaptive capacity. Tidal marshes emerged around the edge of the bay 2,000 to 3,000 years ago, after rates of sea-level rise slowed to 1–2 mm/year. Marshes in south-central San Francisco Bay date from 500 to 1,500 years ago, while expansion of marshes in the southernmost bay dates from 200 to 700 years ago. The earliest stages of salt marsh development indicate instability as sea-level rise gradually slowed. Alternating layers of sediment from that time period (observed in cores taken from deep below present-day marshes) show that marshes were formed, then became mudflats or subtidal areas when the sea level rose, then re-formed again when they were able to build up faster than the rate of sea-level rise. These data indicate that tidal marshes in San Francisco Bay can withstand rates of sea-level rise greater than currently exist (2–3 mm/year), as long as sediment availability is relatively high and other factors, such as subsidence, remain relatively constant.

The estuary's tidal marshes have been responding to wide swings of climate and extreme meteorological events during their 2,000- to 3,000-year history. Analysis of carbon-stable isotopes, pollen, plant macrofossils, and other indicators of salinity in sediment cores reveals that Suisun and San Pablo Bay marshes have alternated

between brackish and saline marsh vegetation over multiple-century intervals of warm and dry or cool and wet climate. The wildlife species associated with these marsh salinity gradients and habitat configurations either adapted rapidly when the climate changed or moved across whole subregions of the estuary, persisting for centuries before abruptly moving again with the next climate shift. Wildlife was able to persist through these large shifts likely due to factors that conferred resilience on the baylands ecosystems, including habitat connectivity, uninterrupted sediment supply, and adjacent transition zone migration space. This history demonstrates that the baylands and their

American avocet



Managed ponds provide diverse habitat functions.



wildlife can withstand significant environmental changes when natural landscape processes are intact.

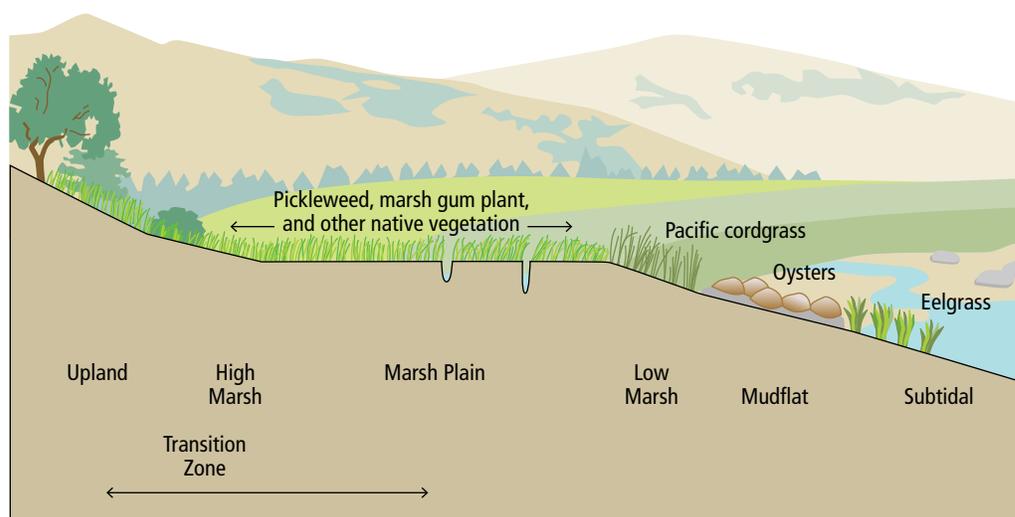
The natural processes that confer resilience on the baylands have been interrupted, altered, and reduced by development and other human activities over the past few hundred years. Human activities have severely constricted baylands habitat extent, fragmented habitat patches, altered sediment supply, and cut off transition zone migration space with levees and development. At the same time, urbanization of the region has created many stressors to wildlife populations. These include contaminants, invasive species, nonnative predators, native predator populations augmented by human food subsidies, and direct disturbance by people and domestic animals. Meanwhile, California's climate since 1850 has been unusually stable and benign, compared to climate variations during the previous 2,000 or more years. Thus, our negative impacts to the baylands have occurred during a time when the baylands have not needed to respond to climatic shifts in order to persist.

A major climatic shift is now under way and is projected to increase in magnitude. To enable the baylands and their wildlife to persist through this shift and provide the ecosystem services the community relies upon, the natural processes that make this ecosystem resilient must be reinstated, enhanced, or replicated. The following sections describe actions that will enhance these natural processes.

Complete Tidal Wetlands

The baylands are a dynamic continuum of habitats connected by physical and biological processes; they extend from the open waters of the bay through intertidal mudflats, tidal marshes, and adjacent terrestrial areas. Less extensive habitat types, such as beaches and rocky intertidal areas, are also important parts of the baylands, and each habitat type has variation and complexity, as well as transitions between it and the adjacent habitat type.

Figure 11 Schematic of the complete tidal wetland system.



Given the complexity of the tidal conditions and freshwater inputs to San Francisco Bay, drawing boundaries between the functions of the open-water bay, mudflats, tidal marshes, and estuarine–terrestrial transition zone is difficult and sometimes arbitrary. A more accurate way to consider this continuum of habitats involves the concept of a “complete tidal wetland system,” which emphasizes all the aspects of the baylands ecosystem and the full gradient of ecological functions and ecosystem services (fig. 11).

Although diked baylands are not natural features, some do provide significant habitat value, particularly ponds that are managed to support wildlife. Restored and extant tidal marshes may not provide all the habitat functions currently provided by managed ponds. Therefore, these managed habitats must be included in any plans for restoring complete tidal wetlands systems.

The concept of complete tidal wetlands systems is discussed more fully in Science Foundation chapter 1, and the many habitat types that make up the baylands are described in appendix E and in the 1999 Goals Project.

Natural Processes Governing the Extent of Marshes

As previously noted, tidal baylands are dynamic and evolve over time. The processes that govern the extent of tidal baylands are particularly important now, given that climate change and other drivers threaten to convert a large proportion of the baylands into subtidal areas that do not provide the same ecosystem functions and services. A number of physical processes that govern the evolution of tidal baylands are defined for this report as follows:

- ◆ *Migration* (also called transgression) is the movement of baylands upslope into their watersheds. Migration is governed by sea level, hydrology, sediment supply, plants, topography, and subsidence.
- ◆ *Erosion* is the loss of tidal baylands due to the loss of sediment from their surfaces or edges. It can be vertical or horizontal. Most horizontal erosion occurs at the boundary between tidal baylands and subtidal areas due to wave action.

- ◆ *Progradation* is the extension of new baylands into the bay when subtidal areas are converted to intertidal elevations. Progradation is governed by sediment supply, intertidal plant and animal populations, and the nature of erosive forces along the boundary between tidal and subtidal areas.
- ◆ *Drowning* is the conversion of baylands to habitats lower in the tidal frame (e.g., marsh changing to mudflat or mudflat becoming subtidal).
- ◆ *Accretion* is the vertical buildup of marshes with inorganic sediment and organic matter (mainly peat). Accretion can prevent drowning and can convert lower tidal baylands to higher tidal baylands. For example, accretion can convert subtidal areas to tidal flats, and tidal flats to tidal marsh, as observed in many restoration projects in the bay.

These processes apply to tidal wetlands systems in general. Here, they are discussed mainly in relation to tidal marsh, which was the dominant habitat in the baylands historically and is now the focus of much restoration effort. The major drivers of tidal marsh evolution are elevation, plants, inorganic sediment supply, peat accumulation, incident wave energy, migration space, and the rate of relative sea-level rise.

Diked baylands are divorced from the natural tidal processes that confer resilience on tidal baylands. Some diked baylands are subject to processes like shallow subsidence (which occurs when organic sediments dry out and oxidize) and wind erosion (which can occur when the desiccated sediments are plowed, raked, disked, or graded). See section, Diked Baylands for more on the future of diked baylands.

MIGRATION AND SQUEEZE

The topography landward of tidal baylands is a key factor in determining how far the baylands can migrate as sea levels rise. Similarly, the width of river and stream channels and the extent of their floodplains determine how far tidal baylands can migrate upstream. Steeper lands, levees, and other constructions along the landward boundary of tidal baylands constrain migration. Where migration is not so constrained, it is influenced by factors that include the relative rate of sea-level rise, suspended-sediment supply, freshwater inputs, the rate of colonization by tidal marsh vegetation, and organic matter accumulation. Terrestrial soils may not be conducive to marsh plant colonization, due to problems with soil fertility, salinity, bulk density, or permeability, which could limit the dispersal and recruitment of vegetation and, thus, the rate of marsh migration.

As the rate of sea-level rise increases, the upland topography adjacent to marshes plays an increasingly important role in allowing or preventing the landward migration of tidal baylands. Eventually the baylands could become squeezed between expanding subtidal areas and steep uplands or built environments with steep levees. The opportunities to accommodate broad areas of evolving tidal baylands due to migration are greatest in the less developed valleys around the bay. Protecting and expanding these opportunities is critical to ensure ongoing ecosystem services from the baylands.

A recent analysis of undeveloped shoreline areas across which baylands may need to migrate, given a 1.4-meter (4.6 foot) sea-level rise, shows that a little over one-third (36 percent) of this area is protected as open space, while the remaining 64 percent is privately held and subject to future residential and commercial development (fig. 12). These results highlight the importance of a holistic and directed effort to identify, plan for, and conserve baylands migration space.

EROSION AND PROGRADATION

The bayward edge of the marsh erodes or grows (progrades) horizontally depending on the energy and direction of waves produced by the wind (wind waves), sediment supply, vegetative structure, and sea-level rise. Mudflat governs many of these conditions at the bayward marsh edge, as the extent and depth of mudflat influences the size and energy of waves reaching the marsh and regulates its contribution as a local source of sediment. Thus, mudflats and marshes are interdependent parts of the complete tidal wetlands system. Mudflats dampen and regulate offshore waves, causing the waves that reach the marsh to be relatively constant in height for a given water depth.

Mudflat slope and shape thus control to some degree the balance between marsh erosion and progradation. A combination of sediment supply and wave energy determines the shape and elevation of the mudflat. If mudflat elevation does not keep up with sea-level rise, more wave energy will reach the marsh edge, leading to erosion and loss of marsh extent.

Drowning and Accretion

The sum of two interconnected processes, inorganic matter accretion and organic matter accumulation, determines the ability of a marsh to grow vertically with sea-level rise. Both processes affect and are affected by marsh elevation relative to the tide. Salinity is also a key driver of organic matter accumulation. Peat accumulates faster in freshwater marshes, and the accumulation rate decreases as salinity increases.

PROTECTION OF TIDAL MARSH MIGRATION SPACE
AROUND THE SAN FRANCISCO BAY

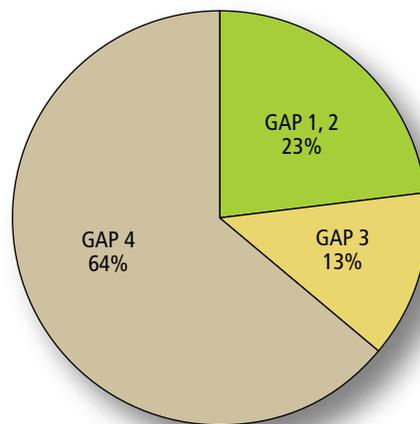


Figure 12 Analysis of GAP (National Gap Analysis Program) status of undeveloped lands within the footprint of the baylands. GAPS 1 and 2 indicate high levels of resource protection, 3 moderate levels, and 4 no protection. Adapted from Kirk Klausmeyer, The Nature Conservancy.

Box 3 Lessons Learned: The Evolution of a Big-Picture Vision of Restoration

The Goals Project advanced the region's collective ability to accomplish ecosystem-scale restoration, despite no one entity having had the resources and expertise to conduct large-scale habitat protection and restoration projects comprehensively. Projects are managed by a range of agencies and nongovernmental organizations on both public and private lands. Therefore, partnerships, coordination, and the application of lessons learned from one project to another are essential.

Restoration practitioners have now completed over 80 distinct habitat restoration and enhancement projects in the baylands. During the course of planning, designing, permitting, constructing, monitoring, and implementing adaptive management, a number of lessons have been revealed:

- ▶ Modeled impacts of habitat conversion have shown that maintaining and managing water levels and salinity in select ponds can be critical to the survival of some of the more common wildlife species.
- ▶ Techniques can be employed to make restored tidal marsh much more beneficial to waterbirds, offsetting the losses of saline pond habitat.
- ▶ In subsided areas, accurate elevation maps are essential for designing future projects and determining whether to add clean fill material.
- ▶ Sediment is an essential resource for raising elevations to marsh plain level in many projects.
- ▶ In some locations, enhancing the existing tidal marshes can be less expensive and can provide direct benefits to wildlife more quickly than can large-scale restoration.

The Goals Project's findings themselves have moved us toward the integrated vision presented in this Science Update, for example by:

- ▶ Documenting 27 miles of sandy beaches in the bay before European development and recommending that these forgotten features be an important component of baylands restoration. We are starting to reestablish beaches, not just for native plant and bird habitat, but also as dynamic, self-adjusting buffers to wave energy.

- ▶ Recommending the establishment of tidal marsh corridors along the salt-to-fresh gradient at the mouths of creeks due to their importance for the delivery of sediment and freshwater. Whether natural or artificial, these nodes are now recognized as some of the most valuable and resilient places for marsh conservation.
- ▶ Emphasizing the importance of the tidal-terrestrial transition zone; in light of sea-level rise, such transition zones are of critical importance to the future of our marshes.

Today practitioners meld these lessons to consider how a project will interact with other wetlands and infrastructure to function as part of the larger landscape.



New Chicago marsh at sunset

There is a strong feedback loop between the inundation regime (frequency, depth, and duration of tidal flooding) and plant productivity, which drives organic matter accumulation rates. Peak plant productivity occurs when the marsh plain is at or just below the marsh plain elevations of stable marshes. As a result, a slight increase in inundation may lead to an increase in plant productivity, as long as the initial marsh plain elevation is above the elevation of peak productivity. A large increase in inundation, on the other hand, would cause plant productivity to decline, leading to a further loss of relative elevation and even greater inundation, because of reduced organic matter accumulation.

This process drives, in part, the recommendation to restore marshes as early as possible, allowing them time to grow as high into the tidal frame as possible, to give them a “leg up” on the sea-level rise that will accelerate in the second half of the century. This leg up is more formally known as *elevation capital*. Elevation capital is determined in large part by comparing the absolute elevation of a marsh with the local water levels and tidal range. Most tidal marshes in the baylands are dominated by mid- to high-marsh vegetation and are at the upper elevation range for tidal marsh ecosystems. Their relatively high elevation gives them substantial elevation capital, which should help these marshes maintain their elevation in the tidal frame for a while.

While accumulation of organic matter is important, especially in the brackish parts of the estuary, inorganic sedimentation is the primary process for San Francisco Bay marshes to accrete vertically with rising sea levels. Inorganic sedimentation increases as a marsh falls lower in the tidal frame and the depth of water over the marsh increases, in contrast to accumulation of organic matter. This relationship is why sediment often accretes rapidly at newly restored sites, especially at sites that are subsided, because mineral sedimentation is much greater at lower elevations. The inorganic sediment supply, which also affects the vertical accretion rate, is a function of the suspended-sediment concentration in the water column, depth of water, and period of high water. Inorganic sediment supply depends on local conditions as much as on the supply of sediment from the delta and other baylands watersheds (particularly via local stream sediment inputs), the resuspension of sediment

from adjacent mudflats, and the suspended-sediment concentration in nearby tidal waters. For inorganic sedimentation, the higher the suspended-sediment concentration and the deeper the water over the marsh, the greater the amount of sediment available in the water column to be deposited. This positive feedback loop can help maintain marshes as the sea level rises, as long as there is sufficient fine sediment.

A well-developed tidal-channel network is important for delivering sediment to all parts of a marsh.

Tidal marsh plants colonizing Mt. Eden Creek mudflat



Mineral sediment deposition is highest closer to tidal breaches and bordering tidal channels, which leads to the creation of slightly elevated natural levees along sloughs. If there is insufficient tidal prism, due to filling of the marsh or diking, then channel networks may not fully evolve, resulting in poor habitat and low accretion rates at the back of the marsh away from the channels. Lowering any bayside levee is also important for delivering sediment to tidal marsh.

Presently, tidal marshes in the bay are accreting enough sediment to keep pace with sea-level rise. Average accretion rates across the region are about the same, although accretion at individual sites varies according to local conditions. Marshes can grow vertically very rapidly, much more rapidly than the average accretion rate, when enough sediment is available and accretion is stimulated by the marsh being lower in the tidal frame—as witnessed by the ongoing need to dredge marinas around the bay. This history of keeping pace with sea-level rise has coincided with a period of relatively low rates of sea-level rise as well as high sediment supply. This period may have ended, judging from a step-change reduction in suspended-sediment concentrations that was recently observed in the estuary (see below).



Complex channel networks are critical to the resilience of tidal marshes.

Key Physical and Chemical Drivers

Several physical and chemical drivers affect both how the processes described above occur and also how the baylands function ecologically. These drivers are summarized below, leading into the analysis described in the section Projected Evolution of Baylands Habitats.

SEDIMENT SUPPLY, DEMAND, AND TRANSPORT

The processes that affect the amount of sediment available to any marsh or mudflat in the baylands are changing. Sediment supply historically increased but has since declined due to human actions in the estuary's watershed. Both the local watersheds around the bay and the delta's watershed are important in determining sediment supply to the bay.

Beginning in the early 1800s, intensive ranching and farming in local watersheds around the bay greatly increased runoff, which initiated a period of chronic erosion



Sediment rich waters enter from the bay.

of the land surface and stream channels that persisted unchecked into the 20th century. Urbanization caused additional increases in runoff and stream erosion. In the mid-1800s, extensive hydraulic mining in the Sierra Nevada mobilized large volumes of Sierran sediment to the eastern, northern, and central areas of San Francisco Bay. Areas of the bay south of the Golden Gate were less directly affected by this large pulse of Sierran sediment, but were still affected by increased local sediment supplies. During this same period, vast areas of tidal baylands were reclaimed for ranching, farming, and other uses. There was, therefore, less intertidal area for the suspended sediment carried by the tides to be deposited and stored. In response, tidal marshes and mudflats rapidly expanded, due to the abundant supply of and diminished demand for sediment. The tidal reaches of rivers and streams shoaled and narrowed, and once naturally deep harbors had to be dredged.

The supply of suspended sediment to the baylands has since greatly diminished. Today, local runoff and land surface erosion are much better managed. Channel erosion, while still a problem for many local rivers and streams, has been curtailed by bank revetment and flow regulation. Sediment entering large and small rivers and streams is often trapped behind dams and in flood-control bypasses. Many of the flood-control channels built during the last half of the past century shunt their sediment directly to subtidal areas, past the tidal baylands that need the sediment to counter sea-level rise. The massive pulse of sediment from Gold Rush mining in the Sierra Nevada has waned. Environmental laws and policies designed to protect the tidal baylands from being diked or filled, and the economics of dredging and transporting sediment, complicate its use to restore or create tidal baylands. Some subtidal

areas of the bay show evidence of getting deeper, due to erosion of the bay bottom. Net erosion or drowning of the tidal baylands is not yet evident. However, one overall effect of current land-use policies and practices is that the supply of suspended sediment for tidal baylands, especially tidal marshes, is less now than anytime in the past 200 years.

The demand for sediment to protect and restore the tidal baylands is increasing. Sediment is needed not only to counter the effects of sea-level rise, but also to restore tidal marshes, which often require significant sediment volumes to achieve the right elevations for sustaining intertidal habitats, particularly in subsided areas of diked baylands. Subsided diked baylands that are accidentally breached will act as large sediment sinks that could detrimentally affect sediment supplies for nearby tidal baylands and restoration projects.

Unfortunately, this reduction in sediment supply exacerbates the problems the baylands face from sea-level rise. Increasing the sediment available to the tidal baylands is probably essential for their survival. An enhanced understanding of the balance between sediment supply and demand, and how that balance is mediated by sediment transport, is critical. A systematic program of investigation could determine where and how sediment should be managed in different subregions of the baylands. For example, a recent study found that the lower South Bay, where suspended-sediment concentrations are high, may have enough sediment to keep pace with sea-level rise if diked baylands are not restored. However, when the additional demand for sediment under various marsh restoration scenarios is factored in, sediment supply may not be able to keep pace with demand. Sediment supply and the actions that can be taken to increase the sediment available to the baylands are discussed in more detail below, in Science Foundation chapters 1 and 2, and in the recommendations chapter that follows this one.

Restoring sediment flows to the baylands.



FRESHWATER FLOWS

Freshwater flow from the delta is the predominant control of the primary salinity gradient in the bay on timescales of a week or longer. It is a critical variable for biological processes. Salinity determines the tidal marsh plant community composition and habitat quality and suitability for many aquatic animals. Delta outflow is positively correlated with the abundance of several key populations of fish and crustaceans in the northern estuary, notably longfin smelt and striped bass, a nonnative but recreationally important fish.

The vast majority of freshwater flow into the bay comes from the delta. Only about 1 percent comes from local streams and wastewater treatment plants. However, these local freshwater inputs often have important consequences for the neighboring baylands. Inflow from the delta results from a complex combination of the quantity, timing, and location of precipitation, snowpack melt, groundwater and reservoir flows, net consumption in the delta, losses to evapotranspiration, and exports from the southern delta.

Future runoff from the Sierra is projected to peak earlier in the year, owing to less precipitation falling as snow and more falling as rain that immediately runs off, along with an earlier melt of the snow that does accumulate. Increasing human population will drive greater demand for the now-reduced summer runoff, possibly leading to more upstream storage and diversion. An increase in human demand for freshwater could be offset to some degree by more efficient water use, the fallowing of lands, or changes in cropping patterns.

Local freshwater flows will have important consequences for the baylands.



TEMPERATURE

Air temperature in the Bay Area is projected to rise. Water temperature will track air temperature in the upper estuary, as it does now. Coastal ocean temperatures, however, may fall as a result of potentially greater upwelling. This contrast would result in a stronger thermal gradient across the estuary from the ocean to the delta in the summer and a weaker one in the winter. However, there is significant uncertainty in projections of upwelling. The severity and duration of extreme temperature events, such as heat waves, are projected to increase, while frost events are projected to become rare locally.

NUTRIENTS

San Francisco Bay has long been recognized as a nutrient-enriched estuary. However, excessive phytoplankton growth and accumulation appear to be controlled here largely by a combination of factors, including strong tidal mixing, light limitation due to high turbidity (muddy waters), and consumption by clams. These controls have helped keep the estuary healthy, maintaining dissolved oxygen concentrations in subtidal habitats much higher, and phytoplankton productivity and biomass substantially lower, than would be expected in an estuary with such high nutrient enrichment. In the future, these controls may be less successful, particularly as the water clears (discussion of decreasing sediment supply above) and water temperatures rise.

Tidal marshes play a role in improving water quality by cycling nutrients. How the baylands restoration will influence nutrient cycling is uncertain due to the system's variability and complexity. However, marshes are known to assimilate nitrogen, particularly in the form of nitrate. Wetlands can be highly effective at removing nutrients from wastewater. Therefore, marsh restoration can help reduce the projected impacts of anthropogenic nutrient inputs to the estuary by retaining and sequestering nutrients. Thus, restoration of marshes may enhance the resiliency of the baylands ecosystem with respect to human inputs of nitrogen.

SEA-LEVEL RISE

Sea-level rise will cause fundamental changes in the nature of the bay and baylands. As previously discussed, sea-level rise necessitates that the baylands and the transition zone migrate landward and upward into local watersheds. If sediment for accretion or space for migration is lacking, then this landward push could result in very narrow strips of baylands along the natural shoreline and levees. Sea-level rise will also move the salinity gradient up toward the delta, allowing ocean water to intrude further into the bay. This happens because deeper water increases the landward penetration of saline waters on the bottom of the bay. This tendency would be enhanced by lower freshwater flow in the dry season.

TIDES

The baylands are strongly affected by tidal waters that move sediment, nutrients, and organisms across habitats. Every few hours tides expose sessile intertidal plants and animals to strongly changing conditions, to which they are well adapted. Large changes in the geometry of the San Francisco Bay, such as would follow a levee failure

Box 4 Planning in the Face of Uncertainty: The South Bay Salt Pond Restoration Project Adaptive Management Plan

We face significant uncertainties in predicting how and when the effects of climate change will be felt along the bay's edge. Land managers, resource agencies, and regulators must develop flexible approaches to planning and permitting to support resilient baylands.

The South Bay Salt Pond Restoration Project (SBSPRP), a large-scale, long-term restoration effort, obtained all the necessary permits for implementation based on an adaptive management plan that commits the project to restoring a range of wetlands habitats. However, the exact mix of habitat types and extent will be determined by what is actually developing on the landscape over the next 40 years. By developing a preferred alternative that commits to a scientifically driven range of outcomes, the SBSPRP provides



a model for a wetland restoration program that constantly takes in new information and adapts to changing conditions in the bay.

Development of the SBSPRP's Adaptive Management Plan

The SBSPRP was launched in 2003 upon the transfer of over 15,000 acres of Cargill salt ponds into public ownership. From the outset of restoration planning, the project partners understood the importance of developing a restoration plan and approach with both scientific rigor and broad public support.

The sheer size of the project required its science and consultant teams to grapple not only with the physical scale of restoration, but also with its progression over a 50-year period. The teams considered whether there was enough sediment in the bay to establish marsh in deeply subsided ponds, and whether marsh accretion could keep pace with uncertain amounts of sea-level rise. Uncertainty over how guilds of bird species would respond to large-scale habitat change similarly led the project partners to realize that the overall restoration plan had to be built on a strong foundation of science and adaptive management.

Early on, the issue of how much pond habitat to manage versus how much marsh development to encourage became foundational to the entire restoration effort. The participants issued a series of white papers on key scientific uncertainties facing this large-scale project over time and developed the concept of creating "bookend" alternatives for

A small dredge lock on Pond M12

in Suisun or the delta, would change tidal action, probably reducing it in many areas. A loss of tidal action, plus more ocean intrusion from sea-level rise and less freshwater flow, could shift parts of the bay toward a more lagoonlike system that is less directly coupled to river outflows, as currently seen in the lower South Bay.

California Environmental Quality Act (CEQA) purposes that establish ranges of restoration targets rather than specific targets. The determination of restoration targets as well as triggers for management action was predicated on this approach.

In the project's Environmental Impact Report and Statement, the high end of the projected range for tidal marsh restoration (90 percent) was set out as the preferred alternative. This was paired with a scientifically driven process to assess success along a continuum that remains at the heart of the approved adaptive-management plan.

Principles for Future Planning

The experience of developing and implementing the SBSPRP showcases four principles for Bay Area agencies and stakeholders to consider as they plan how to address sea-level rise and other drivers of change around the bay:

1. Plan for uncertainty: Allow agencies that are in the position of planning for or permitting future bay restoration or flood-management actions to use scientific and community stakeholder input to develop ranges of desired outcomes.
2. Increase tolerance for failure: One of the best successes coming out of the SBSPRP was that the project partners agreed to scientifically driven management that adapts to site conditions over time.
3. Support science and monitoring: Real adaptive management requires a commitment to learning through the funding of long-term science and monitoring. The expense and commitment of this approach may require both resource and regulatory agencies to consider innovative mechanisms for funding these efforts. The importance of monitoring

needs to be made abundantly clear to funders, and barriers to funding need to be addressed.

4. Organizational transparency: The success of the SBSPRP to date is a result of the commitment of the project partners to ongoing organizational learning, active public participation, and transparency of both the planning and implementation processes. As one member of the project management team stated, it requires that a critical mass of partners be committed to continually "tend the consensus" to keep everyone on board.

Implementing these principles is easier said than done. A SBSPRP management team grapples continually with maintaining the long-term vision, funding the needed science, and tolerating unanticipated short-term outcomes on the landscape. The shared understanding of the adaptive-management approach needs to be constantly reinforced and revisited over time. Agency personnel and leadership can change, funding sources decline or change, and active community stakeholders change over time as well. Long-term adaptive management therefore requires a steady commitment on the part of all parties to recommit resources over time.

Most future wetland or coastal restoration projects in San Francisco Bay will be smaller in scale than the SBSPRP, and may not have the capacity to track large-scale climate change or population trends. This constraint will require regulators and policy makers to think creatively about how to measure and analyze trends in the bay across multiple small restoration efforts. Agencies and their stakeholders will have to cultivate flexibility and a higher tolerance for the possibility of failed experiments or ambiguous outcomes—on the promise of ending up on a more sustainable trajectory over the long term.

STORM EVENTS

An increase in the frequency of intense storms due to climate change could physically affect baylands habitats through flooding and erosion. Large storms create higher water in the bay from storm surge and freshwater outflow. Also, storm winds can cause higher waves in the bay, which reach the baylands with more energy because of the increased water depth. Thus, more intense storms could generate more powerful wind waves that increase erosion of the baylands. More erosion could occur both at the bayward edge of marshes and at the landward edge during very high tides.

PROJECTED EVOLUTION OF BAYLANDS HABITATS

The dynamic processes and key drivers that govern baylands evolution operate on multiple timescales, with some outcomes requiring decades to be fully realized. To sustain the local baylands ecosystem functions and services in the long term requires planning, preparation, and implementation in the near term. Thus, projections of what the baylands will look like after the drivers of change have influenced their evolution are necessary to guide decisions about which management actions to set into motion. This section summarizes the latest science on how the baylands are likely to evolve under different scenarios (see section Future Scenarios Evaluated, above) and details the types of actions that can be taken to influence that trajectory. It builds on detailed information found in Science Foundation chapter 2.

Tidal Baylands

The evolution of tidal baylands habitats could progress in a number of ways: through equilibration/dynamic stability, gradual evolution, or collapse.

- ◆ **Equilibration/dynamic stability.** Existing tidal marshes accommodate sea-level rise with a minor long-term conversion of tidal habitat types and a gradual landward migration. Gradual (historic) rates of sea-level rise and net-positive sediment budgets result in relative resilience. This stability is not likely to occur in a regime of rapidly increasing sea-level rise and neutral or negative sediment budgets.
- ◆ **Gradual evolution.** Tidal marsh habitats gradually submerge, with the following habitat-type conversions: high marsh transitions to mid marsh, mid marsh to low marsh, low marsh to mudflat, and mudflat to subtidal. Tidal marsh pans expand and tidal channels enlarge. The bayward marsh edge undergoes a progressive but slow erosional retreat, creating wave-cut marsh “cliffs,” or scarps. The landward marsh edge experiences either levee overtopping, erosion, and breaching, or levee raising, armoring, and additional artificial bayland drainage (such as ditches). The “gradual evolution” progression is compatible with coastal climate-change adaptation through modification of the baylands.
- ◆ **Collapse.** Marshes convert abruptly to mudflats and subtidal areas. This worst case is associated with an early onset of sea-level rise at the upper end of projected rates. Sea levels would overstep marsh platforms, causing the wholesale drowning of marshes. Marsh plains initially respond by converting to low marsh but are ultimately lost as rapid marsh vegetation dieback creates extensive pans that “swallow” fragmented marshes, converting them to tidal flats. This is analogous to the contemporary tidal marsh loss in Elkhorn Slough in Monterey County, the Gulf of Mexico, and the Mississippi Delta. Rapid marsh-edge and levee erosion, increased flooding of diked baylands or undiked adjacent lowlands, and the rapid loss of critical high-marsh and transition zone habitats are likely to occur.

The next 50 years will probably see a variable mix of equilibrium/dynamic stability and gradual evolution, unless the sea-level rise rapidly increases due to abrupt changes in ocean temperature or ice-sheet collapse. Maintaining the existing marsh



Marsh and mudflat processes will experience changing equilibrium.

zones with no conversion would be an optimistic projection, because as marsh plain drainage decreases with submergence, so does marsh plant growth and vegetation height. Reduced marsh vegetation growth will mean less stem height and density for trapping and stabilizing suspended sediment and less production of organic matter in the soil.

Events like storms, droughts, and earthquakes that cause change in baylands habitats will probably punctuate any mix of equilibrium/dynamic stability and gradual evolution with more abrupt changes in particular locations. Erosion caused by more intense storms may be significant in some areas. In general, over the next century we expect climate change and other drivers to create a more dynamic landscape, with the location and nature of baylands habitats shifting more frequently than in the recent past.

RESULTS FROM MARSH-ACCRETION MODELS

The balance between sea-level rise and rates of marsh sediment accretion is critical to marsh sustainability. Several recent modeling efforts have investigated this balance, using different models, sites, and input parameters. All the results from these models are sensitive to the rate and magnitude of sea-level rise and the supply of sediment to the marsh. The future numeric values of both variables have uncertainty. The models were relatively less sensitive to the different scenarios tested for organic sediment accumulation.

Like all other models, they involve assumptions and structures that are simplifications of the complex processes in the natural world. Thus, between the uncertainty in the sea-level rise and sediment-supply input parameters, and the uncertainty inherent to the structures and assumptions, the models do not indicate what will happen. Rather, they provide a projection based on the best available science, with an output falling within a range of uncertainty.

The Marsh98 model, with the most comprehensive geographical coverage of the bay, was part of the basis of scenarios 1 through 4 (see Future Scenarios Evaluated). Across all sea-level rise and sediment-supply scenarios, the model projects an increase in mid-marsh habitat between 2010 and 2030 throughout the estuary, partly at the expense of high-marsh and upland habitat (fig. 13).

Between 2030 and 2050, the model projects an increase in low marsh and a decrease in high marsh and upland across all scenarios. For the high sea-level rise/low-sediment scenario (scenario 3), mid marsh also declines. In general, the area of tidal marsh is projected to remain relatively unchanged between 2030 and 2050, but the composition of the marshes is likely to change, with more low marsh and less mid and high marsh.

The outcomes of scenarios 1 through 4 become quite different when projected to 2110. The model projects an increase in mid marsh for low sea-level rise under either sediment assumption and for the high sea-level rise/high-sediment assumption (scenarios 1, 2, and 4). In contrast, the model projects a conversion of more than 90 percent of mid marsh and high marsh to low marsh, mudflat, or subtidal habitat in the high sea-level rise/low-sediment scenario (scenario 3). The model shows opportunities for unimpeded marsh migration, with 5,000 to 7,500 acres of currently terrestrial habitat potentially evolving to tidal marsh by 2110, depending on the scenario.

The potential impact on specific marshes can be seen in the Marsh Equilibrium Model (MEM) projections for China Camp (fig. 14). Increasing the rate of sea-level rise and decreasing the availability of sediment results in a greater loss of relative marsh elevation, with mudflat being the ultimate outcome in 2110 under the worst-case scenario.

The 2012 National Research Council report shows a projected range of sea-level rise between 40 centimeters (1.3 feet) and about 1.6 meters (5.4 feet) at 2100 for San Francisco Bay. The high and low ends of this range have very different ramifications for what happens to the marshes. Across various models, the results agree that at a low sea-level rise rate (e.g., 50 cm/century), the marshes can keep pace with the sea level, even with low sediment availability. However, with a sea-level rise greater than 100 cm/century and low sediment supply, there will be a decline in mid- and high-marsh habitat.

Diked Baylands

Many parts of the bay are not fully tidal, which limits their ability to evolve because they are isolated from the tides and the sediment the tides carry. The baylands were typically diked by constructing earthen berms along the margins of the marsh plains where they bordered mudflats or large tidal channels. The major types of diked baylands are diked wetlands (including duck clubs and other managed marshes), agricultural baylands, salt ponds, and managed ponds (which include storage and treatment ponds and ponds managed for wildlife). Salt ponds are located in the South Bay, managed ponds are largely in the North and South Bay, duck clubs in Suisun, agricultural baylands in the North Bay, and water-treatment ponds in the Central and South Bay.

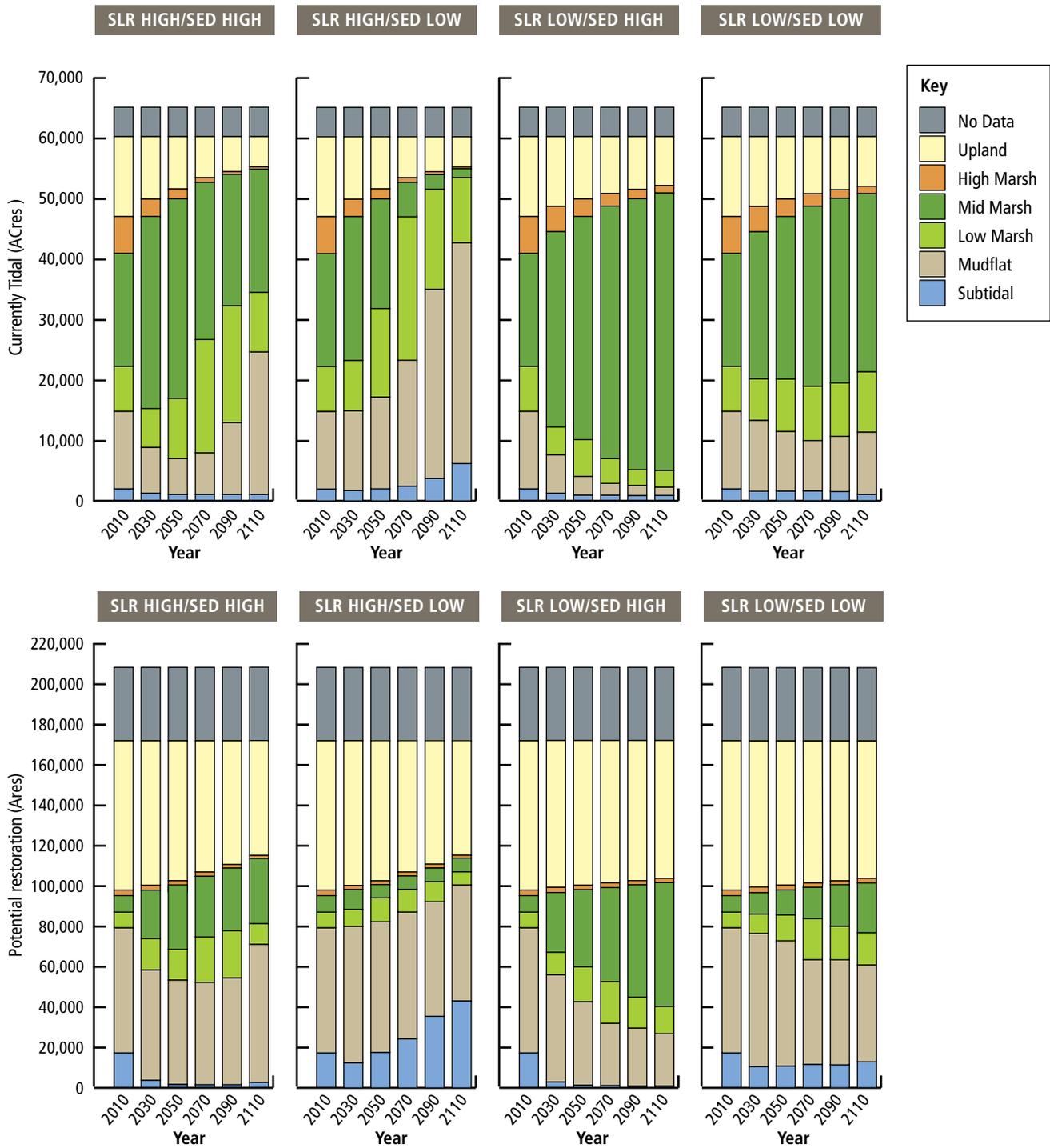


Figure 13 Results from the Marsh98 model showing projected marsh habitat extents under different sea-level rise (SLR) and sediment supply (SED) scenarios for both current tidal areas and potential restoration areas. Note the different y-axis scales. Adapted from Stralberg D et al (2011). Evaluating tidal marsh sustainability in the face of sea-level rise: a hybrid modeling approach applied to San Francisco Bay. *PLoS ONE* 6(11): e27388.

Although diked baylands are not natural features of the bay, some of them do provide significant habitat value that may not be fully replicated in tidal marshes, even if the goal of 100,000 restored acres is achieved. In addition to ponds managed for wildlife, diked baylands include duck clubs, muted tidal marshes, treatment wetlands, and mitigation wetlands. Diked habitat types and the wildlife species they support vary greatly, from large duck clubs to small mitigation projects to support endangered species such as the salt marsh harvest mouse. Diked baylands also feature significant urban areas, including airports and entire cities, and agriculture from hayfields to vineyards. These developed diked baylands weigh heavily in the planning for sea-level rise, requiring additional protections or land-use conversions that will shape opportunities for future baylands restoration and wildlife support.

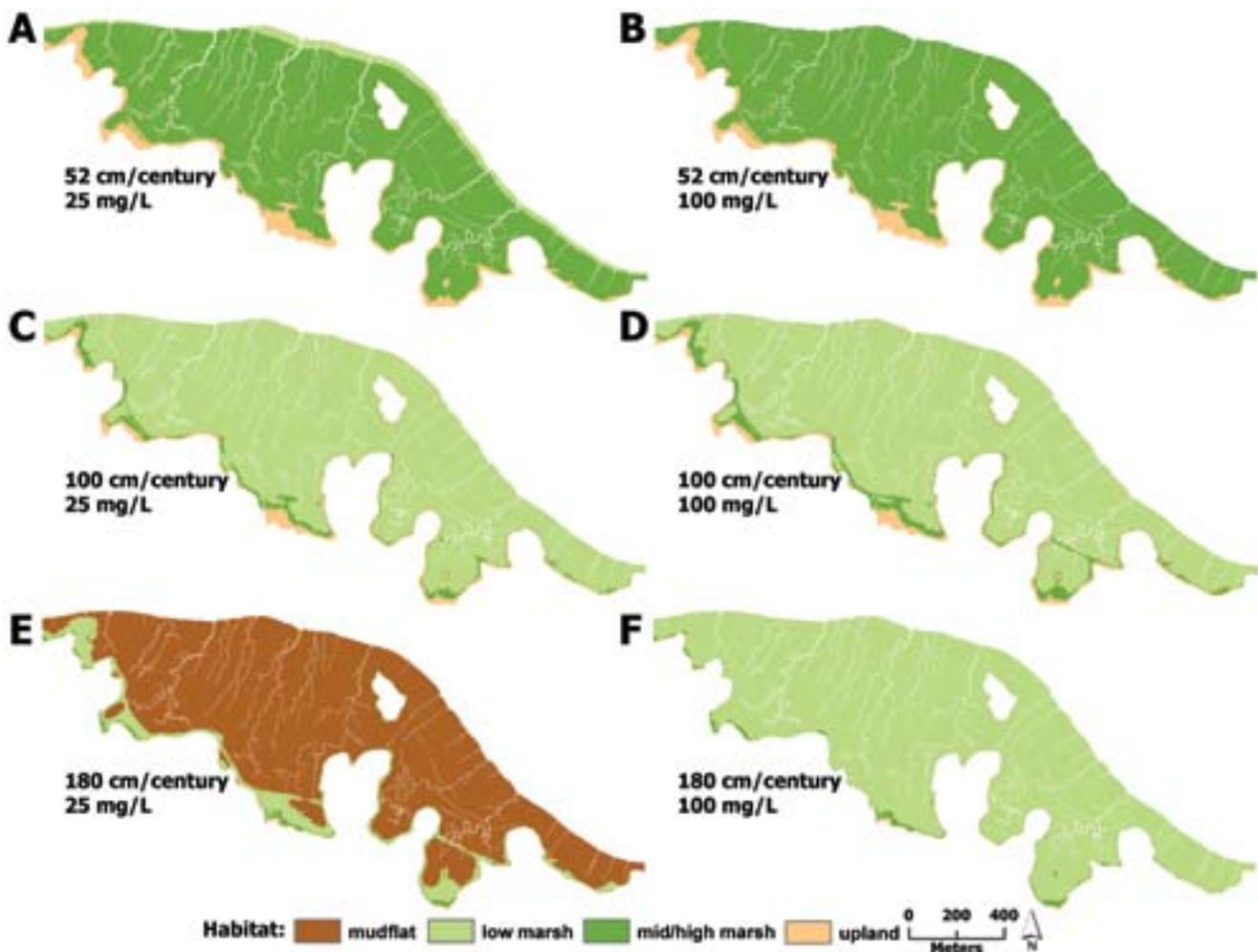


Figure 14 Distribution of modeled habitat types in 2110 from the MEM projections at China Camp marsh for various rates of sea-level rise (in centimeters per century) and suspended-sediment concentrations (in milligrams per liter). From Schile et al (2014). Modeling and marsh distribution with sea-level rise: evaluating the role of vegetation, sediment, and upland habitat in marsh resiliency. *PLoS ONE* 9(2): e88760.

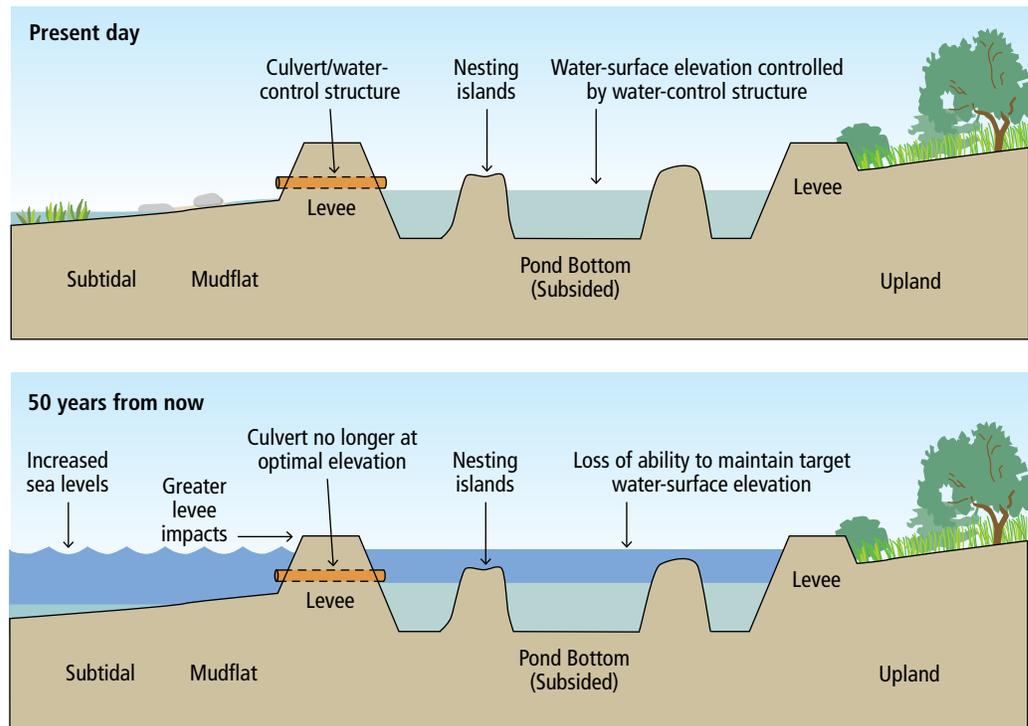
The effects of climate change, particularly sea-level rise, challenge the long-term viability of managed baylands habitats. It is prudent to minimize reliance on managed systems, as these ponds are spatially fixed features in a bay that is dynamic and moving landward. Managed ponds in public ownership are already experiencing technical and financial challenges to sustain their expected performance. Even under low to moderate sea-level projections, the functionality of these managed systems will become increasingly difficult to sustain.

To control water levels and salinities inside the ponds for target species, the water-control structures and levees usually require specific elevations for water intake and outlet points. Intake water for managed baylands comes from the bay or adjacent freshwater sources, depending on the location and habitat goals of that pond. Climate-change-related stressors, such as higher water levels, a greater frequency and intensity of storm events, and regional salinity shifts, may make it difficult or even impossible in the future for managers to maintain target habitat conditions inside the ponds (fig. 15).

Considerations for Actions Related to Habitat Evolution

The following discussion details the considerations the science contributors looked at when developing recommended actions to take in response to the scientific findings summarized in the earlier parts of this section. The appropriate application of these actions will vary across the baylands depending on particular physical, chemical, and ecological settings. In each section of this science summary, we provide a brief introduction to the recommended actions relevant to that section, so that the reader can trace the scientific basis of the recommendations.

Figure 15 The impact of sea-level rise on managed ponds over time, from the present day ($T=0$) to 50 years from now ($T=50$). Water-surface elevation is controlled by the water-control structure.



TIDAL BAYLANDS

As sea levels rise, the extent of tidal marsh and mudflat can be influenced by the management of sediment supply and accretion, shoreline stabilization, space for landward migration, and the elevation capital of marshes. These are mostly relatively new variables for restoration and planning efforts, requiring a significant change in common practices.

Vertical Accretion and Elevation Capital

Management actions can increase the vertical accretion rate of marshes by increasing the supply of fine sediment, improving the pathways by which the sediment arrives to various parts of the marsh, or increasing the trapping of sediment on the marsh. Fine sediment can be introduced directly into the water column (a water-column recharge), on the marsh surface, or on the mudflat to be later resuspended by wave action and deposited onto the marsh by tidal and wave processes (a mudflat-and-marsh recharge). Direct placement of sediment in subsided areas has been done successfully in several areas of the bay, capturing 100 percent of the sediment placed. However, it is expensive to do. Recharging the water column and mudflats has considerable benefits, allowing the choice of when, where, and how much sediment to introduce into the system. However, mudflat and water-column recharges are untried in the bay and present significant permitting challenges, as they could have detrimental impacts to existing habitat and organisms.

Sediment sources from the landward side of marshes could be exploited as well. Options include placing clean fill material directly in subsided areas and changing watershed management practices to increase sediment inputs to the marshes or the bay. Significant amounts of sediment are trapped behind dams, and learning how to safely access and move those sediments and other watershed sources to the bay is worth consideration. Streams could be managed to sustain flows after a storm so that they transport silts and clays all the way to the bay. These types of changes to watershed management may require significant research into ways to increase sediment delivery to the bay without harming stream habitat or affecting management goals.

Sediment transport can be enhanced by reconnecting creeks and rivers to the landward side of marshes. Terrestrial sediment loads from local tributaries can contribute to local marsh accretion and extend natural river levees into tidal marshes (figs. 16 and 17). For example, the tidal marshes of Bolinas Lagoon persist or regenerate in confined reaches of the lagoon where sediment deltas are deposited by creeks. This pattern could be a guide for more resilient shoreline types in the bay; the alluvial fans of today are the tidal marshes of tomorrow. Sediment transport can also be enhanced by ensuring that marshes contain tidal channels of sufficient size and density to convey fine suspended sediment from the bay to the landward portions of the marsh, as well as by lowering any bayside levee. A co-benefit of complex channel networks is that they protect water quality by promoting circulation and maintaining adequate dissolved oxygen for aquatic species, while minimizing toxicity (pH and ammonia) and mercury methylation.

The trapping efficiency of fine sediment can be improved by increasing the density of vegetation through plantings, by constructing sedimentation fences or similar

Figure 16 Example of a broad natural levee extending into former tidal marsh



Figure 17 Example of a supratidal area caused by flood deposits of sediment on top of tidal marsh

Key	
	Flood deposits of alluvial sediments over marsh
	Wildcat Creek



features to emulate vegetation, and by retaining waters on the marsh surface for an extended period of time to allow more sedimentation to occur.

Restoration of tidal marsh can be timed and located to maximize elevation capital and long-term persistence. The timing is simple: the sooner the better, and ideally before 2030. Sea levels are projected to begin rising much more rapidly around midcentury. The sooner that diked baylands are restored to the tides, the sooner they can begin accreting inorganic sediment, and the sooner they can vegetate and begin accumulating organic matter. If sediment supplies are continuous, marshes established before 2030 will have 20 years to build up elevation capital while rates of sea-level rise

remain moderate. Ideally, marsh plains would be a little higher than the maximum plant-productivity elevation (see Drowning and Accretion) before rising sea levels challenge them to accrete vertically as rapidly as possible. Marshes that can increase plant productivity may be able to keep pace with rising waters longer.

The siting and scale of restoration projects could include careful consideration of both long-term sediment supply and the tidal energy that influences sediment transport and deposition. Areas of the bay that have high concentrations of suspended sediment and a recent history of rapid accretion rates could be prioritized for tidal marsh restoration. Such areas include the deltas around rivers and streams with high sediment loads.

Planning for restoration actions and for the evolution of policies and regulations should also consider long-term sediment supply. Restoration managers can work with dredging projects that have both sediment availability and a regulatory requirement to reuse dredged sediment annually. Practitioners can begin accumulating and stockpiling material (either dredged material or upland fill) now for future use. Also, the innovative approaches discussed above need to be tested, monitored, perfected, and demonstrated in the local setting, which will require some changes in current policies and regulations.

Shoreline Stabilization Measures

The intent of these approaches is to slow the loss of tidal marsh due to erosion at the bayward edge, allowing the marsh to maintain its width for a longer time. Marsh erosion can be slowed through wave attenuation, which decreases wave energy on the marsh edge. Wave attenuation over the mudflat can be enhanced by elevating mudflats, increasing the bottom friction of the mudflat by planting submerged aquatic vegetation, and constructing low-crested breakwaters or berms, including living shoreline elements, such as shellfish beds. The marsh edge could be armored with a beach constructed of relatively coarse material and then stabilized with structures such as groins and headlands constructed of large woody debris or rock.

Coarse gravel beaches are a natural form of shoreline that can adjust to local wind-wave conditions and water levels even during extreme wave events. Unlike

typical engineered revetment systems, such as riprap, the movement of cobble and gravel is an inherent characteristic of a coarse beach and not an indication of failure. Coarse beaches tend to erode less than fine-sand beaches, even gaining material in some cases. The sloping, porous coarse beach, once prevalent in the Central Bay, is able to dissipate wave energy by adjusting its shape in response to the prevailing wave

Enhancing channel and sedimentation dynamics will improve long-term marsh resilience.



conditions. This approach would provide the geomorphic foundation for a gradual migration and ecological transition of native vegetation and habitats associated with the bayward marsh edge.

Low-crested berms constructed from coarse gravel or oyster shell are potential alternatives to conventional armored breakwaters. These would be able to accommodate a rising sea level by naturally rolling landward, driven by wave forces. They may also enhance rather than conflict with ecological and aesthetic objectives for tidal wetland systems and provide additional recreation benefits. For typical nearshore conditions in the East Bay, such berms could reduce wave heights by 10 to 70 percent during normal tidal conditions, which could significantly reduce horizontal erosion rates. The height, width, length, and distance offshore of the berms would determine the amount of wave attenuation and the amount of marsh they would protect.

Migration-Space Measures

Future migration space for the baylands is contained in the estuarine–terrestrial transition zone. Below, *Connections to the Watersheds: the Estuarine–Terrestrial Transition Zone* details ways to create and restore the transition zone to foster landward migration of the baylands.

Another strategy complementary to restoring and creating a transition zone is to realign bayfront flood-risk-management levees further inland to allow marshes and mudflats to transgress landward naturally. Realignment takes advantage of the physical protection provided by marshes and mudflats to reduce the risk of flooding and

P E R S P E C T I V E S F R O M T H E S T E E R I N G C O M M I T T E E

Box 5 Planning to Implement Recommendations for Regional and Subregional Goals

The Science Update recommends that restoration projects be coordinated at the regional and subregional scale. The 2003 acquisition of 15,500 acres of Cargill ponds enabled restoration planning to take place at a subregional scale, with the South Bay Salt Pond Restoration Project representing about 90 percent of the restoration opportunities in the South Bay.

Coordinated planning between project sites in other subregions of the estuary is more challenging, as projects are smaller in acreage, are managed and funded by a variety of land managers and restoration partners, and don't have the advantage of simultaneous timing for funding, planning, and permitting.

Where coordinated planning isn't always feasible geographically, it can be achieved programmatically. Resource managers representing more than 25 landowning and scientific partners of the San

Francisco Bay Joint Venture have been using a structured decision-making process to predict and analyze implications of habitat-management decisions that implement the Goals Project recommendations, both near term (present through 2029) and longer term (2030–2100). Climate-change projections and expert elicitation informed a process that led to measurable attributes, resource allocation implications, and, for the first time, quantified predictions and trade-offs to address climate change in multiple habitats.

Such decision-support tools and models can build confidence in management decisions on a regional and subregional scale. Concurrence of measurable targets of biological integrity can inform true adaptive management and become the basis for informing trade-offs and prioritizing investments both regionally and subregionally.

erosion, allowing smaller levees to be built (fig. 18). The presence of a tidal marsh can reduce storm-wave heights at the landward edge by over 50 percent, depending on water depth and marsh width. Thus, tidal marsh with a smaller levee at the landward edge can provide the same level of flood protection as a larger levee not fronted by tidal marsh. It may be more cost effective to build a flood-risk-management system that incorporates a tidal marsh than to build only a conventional earthen levee.

DIKED BAYLANDS

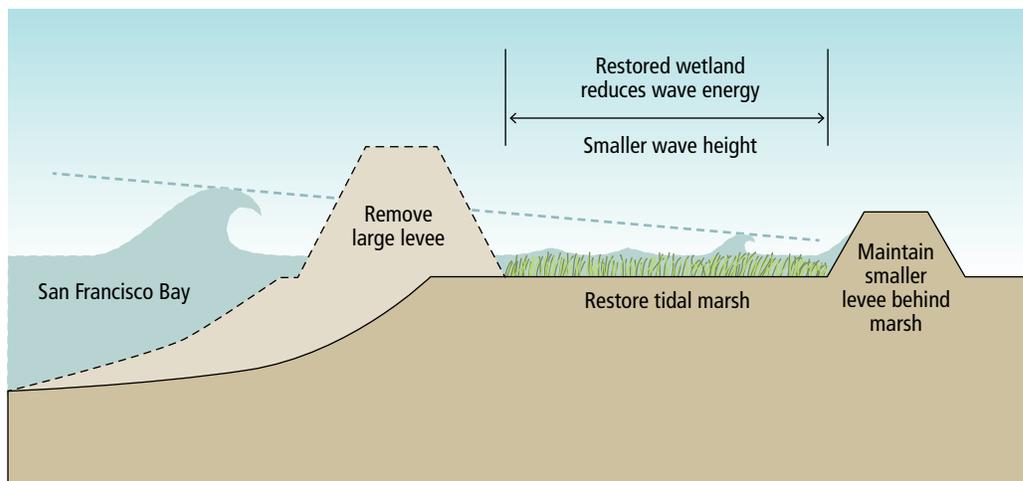
Management actions, some of them novel, will be needed to sustain target habitat conditions inside managed ponds and marshes over time. Levees will come under pressure, either due to increased overtopping of the crest or direct erosion of the levee itself. The most immediate action would be to raise or reinforce existing levees to keep unregulated tidal waters out and retain the ability to control internal water levels. Another approach would be to take advantage of outboard tidal marshes or other site-specific protection opportunities where there are opportunities to do so.

Furthermore, to sustain water-management capabilities, water-control structures would probably have to be modified, added, or replaced, and managed ponds and marshes may become more reliant on the pumping of water as opposed to more passive gravity-driven configurations. In more extreme cases, managed retreat may be appropriate for some of these areas, requiring the relocation or abandonment of diked baylands in areas of higher threat from sea-level rise. Abandoned ponds could then be converted to other (likely tidal) habitat types, after the need for additional flood protection at the specific location is evaluated.

Innovative approaches to making managed ponds and marshes more resilient could be pursued for retrofitting existing diked baylands or constructing new ones. These might include designs for more flexible water-control structures or water-management configurations that can accommodate changes in sea level. Also, there may be ways to allow the bathymetry of managed ponds and marshes to rise with sea levels by capturing sediment, which could ameliorate the need for reinforcing levees and pumping water.

Habitat types will naturally shift over time due to sea-level rise, salinity changes, and restoration. To ensure that the habitat needs of waterbirds are being met, a

Figure 18 Example of a levee realignment, coupled with tidal marsh restoration



large-scale, long-term planning and monitoring effort across the bay, delta, and Central Valley (and ideally the rest of coastal California) is needed. The reliance of Pacific Flyway waterbirds on baylands habitats is partly due to the extensive loss of wetlands in the Central Valley (particularly the delta) and other parts of coastal California. For more on this topic, see Science Foundation chapter 5.

MANAGEMENT ACTION STRATEGY

Choosing which actions to implement will require a consideration of trade-offs between competing uses, near- and long-term benefits and impacts, and which ecosystem services are protected and to what degree. Ultimately, successful implementation will involve adaptive management, defined as a rigorous process of learning by doing and using the results to improve subsequent management actions. Because our knowledge of natural and social systems is incomplete, these systems can respond in unexpected ways. Given this reality, many gaps in data can be filled only by implementing actions and monitoring their performance over the long term.

For example, as part of the restoration of former salt ponds over the past decade, salinities in the North and South Bay managed ponds were purposefully reduced, precipitating a redistribution of the shorebirds that thrive on brine flies and brine shrimp to the remaining salt ponds (which continue to have high salinity). To compensate for such changes, and in anticipation of the ongoing evolution of breached ponds toward tidal marsh, a few managed ponds were enhanced to support greater waterbird numbers in smaller areas. Two such ponds, A16 and SF2, now support very dense avian populations and are a testament to the potential for using science to carefully design restoration and management to meet the ecological needs of baylands wildlife as the landscape changes.

A management-action strategy will need to be developed for each stretch of the shoreline, at the scale of the segments described in the following chapter or even smaller reaches. The strategies will likely consist of multiple actions to be implemented in a number of phases dependent on the amount of sea-level rise (fig. 19). The first phase provides immediate ecological benefits that will enhance the existing baylands and maximize their resilience through years 2050 to 2070, when sea-level rise rates will still be relatively low. The second phase prepares the baylands for the increasing rates of sea-level rise expected after 2070 that may outpace vertical accretion. This is when marshes will need to migrate landward to survive. The recommended actions for each baylands segment in the following chapter initiate this planning process by providing near- and long-term visions and the accompanying actions to take. Action plans for each marsh can then be built out from the more general segment plans.

In the near term, the priorities should be to (1) enhance the resilience of existing marshes by increasing sediment accretion and reducing erosion, (2) expedite the restoration of marshes, and (3) creatively retain or enhance the ecological functions of the other baylands habitats, including the estuarine–terrestrial transition zone, subtidal–intertidal transition, and managed ponds. Pilot studies are crucial to understanding and optimizing the efficacy of various innovative techniques, so that future implementation actions can more readily achieve project goals.

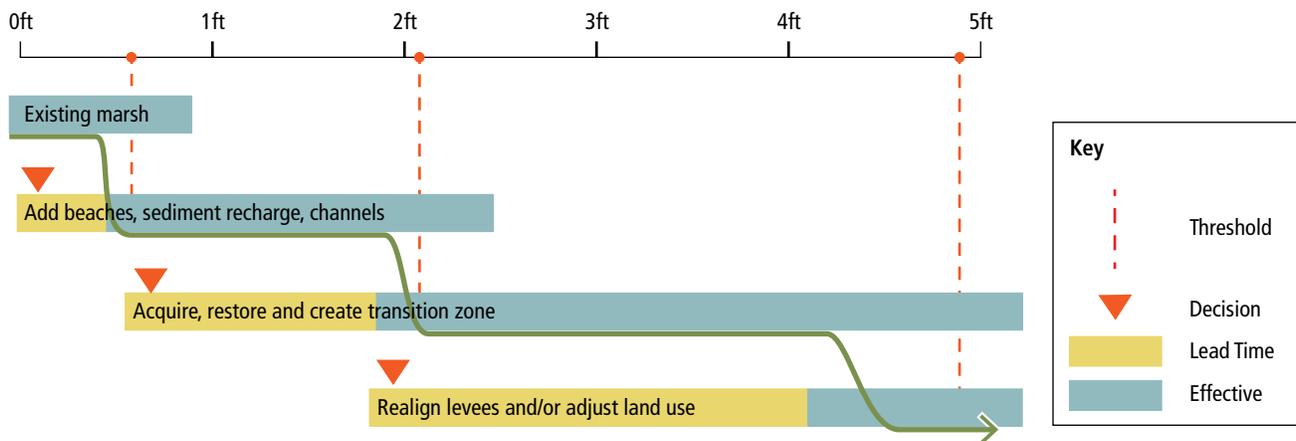


Figure 19 Conceptual phasing of adaptation measures triggered by changes in sea level, rather than a chronological timeline. Because many of the management actions have long lead times for planning, permitting, and construction, decisions about how and when to implement them will have to be made well in advance of when they are needed.

In the longer term, it will be necessary to focus even more on restoring and creating transition zones as well as realigning levees. Coordination with other nonecological shoreline adaptation activities with a potential to affect the baylands will be critical. Successful pilot studies performed in the near term should be scaled up as appropriate, and regional coordination on multipurpose projects and appropriate habitat trade-offs should be explored.

Successful implementation of a management-action strategy will require working closely with the regulatory community to find ways to allow for new and creative solutions when project objectives are to restore or sustain baylands habitat extent and function. Implementation will also require addressing technical factors while also pursuing detailed analyses of costs and benefits, ecosystem service co-benefits (improved water quality, flood protection, recreation opportunities, etc.), the impacts to land use, flood-protection requirements, available and required funds, the policy and regulatory context, and other considerations.

CONNECTIONS TO THE SAN FRANCISCO BAY

The open waters of the bay link the baylands to each other, to the major rivers through the Sacramento–San Joaquin Delta, and to the Pacific Ocean. We refer to these links collectively as the Bay Connection. The following discussion summarizes our current understanding of this connection, building on detailed information found in Science Foundation chapter 3.

The Bay Connection brings the effects of remote changes in the watershed and the ocean to the baylands. The bay and baylands are linked dynamically through the movement of water, sediments, and nutrients (see discussion above in *The Dynamic Workings of the Baylands*), as well as organic matter and organisms. These links provide mechanisms by which changes in the atmosphere, ocean, and watershed can influence the bay and thereby the baylands.

Infrastructure decisions can be made in the context of a phased approach to adaptation.



The movement and net flux of organic matter and organisms between the bay and the baylands is a complex relationship that varies by location and over time. The exact details of the exchange processes depend on the physical configuration of the marsh, including the residence time of water and the kinds and abundance of producers and consumers within the marsh, especially of transient organisms. Few of these aspects have been examined thoroughly in marshes of the San Francisco Estuary.

Long-term studies of the channels of Suisun Marsh have revealed much about fish assemblages, jellyfish, and some zooplankton. A general conclusion from this work is that the channels of Suisun Marsh are largely isolated from the rest of the estuary and that, presumably because of long residence times here, the assemblages of species are somewhat distinct from those of the nearby open waters. On the other hand, the South Bay Salt Pond Restoration Project has documented large numbers of juvenile fish in managed ponds restored to the tides just a few years after breaching, as well as very high productivity of invertebrates such as shrimp as soon as one year after breaching. This high productivity is apparently exported to the open waters through the consumption of small fish and invertebrate prey by predators with larger home ranges in South Bay.

Under present conditions, the delta supplies freshwater that opposes the upstream movement of ocean salt intrusion, nutrients largely from wastewater treatment plants, phytoplankton that subsidizes the low-productivity brackish region of the northern estuary, and zooplankton from freshwater into the brackish region. The Gulf of the Farallones is likewise connected to, and not particularly distinct from, the marine-influenced Central Bay in terms of biota and physical processes. Exchanges between the Central Bay and the Gulf of the Farallones export low-salinity water, sediment, and estuarine organic matter and organisms from the estuary while importing coastal sediment, nutrients, organic matter, and organisms into the estuary.



The Bay Connection links open waters to the baylands.

Future Change in the Bay Connection

Habitat types, their extent, and their quality, as well as the wildlife populations and communities of the Bay Connection, are likely to change under future scenarios. This section draws on several case studies of estuarine organisms and biological communities that consider the effects on each group (see table 1, which summarizes all the case studies used in the Science Update).

EFFECTS OF OCEAN CHANGE

The pH of ocean water is decreasing (commonly referred to as ocean acidification) as a consequence of a greater flux of carbon dioxide from the atmosphere and the subsequent formation of carbonic acid. Relatively acidic ocean water will flow into the estuary, but it is not clear whether the overall range of pH will shift enough to affect biota. The effect of acidification will be complicated by high short-term and small-scale variability. Any persistent decrease in pH is likely to impair calcifying organisms, notably native oysters, which may be particularly sensitive in the larval stages (see oyster beds case study—and all other Bay Connection case studies mentioned below—in Science Foundation chapter 3, appendix 3.1).

Upwelling brings cool, nutrient-rich, low-oxygen, low-pH water to the surface and promotes phytoplankton blooms in the coastal ocean. Estimates of recent climate-related trends in upwelling and projections of future upwelling have been equivocal, but the

past several decades have seen an upward trend. Increased upwelling could increase the nutrient supply for plants and algae in the estuary. It could also bring in large numbers of diatoms and other plankton that thrive in upwelled waters. Low-oxygen events associated with pulses of upwelled water have been observed in South San Francisco Bay since 2006, possibly linked to the observed expansion of the oxygen minimum zone (OMZ) off the Pacific Coast.

EFFECTS OF CHANGES IN SEA LEVEL, SALINITY, AND EXTREME EVENTS

Beds of submerged aquatic vegetation (SAV) interact with sediment supply. Their maximum depth is limited by light penetration and therefore turbidity, but they also trap and stabilize sediments. Like marshes, SAV beds can presumably migrate upslope as sea levels rise, but that depends on local bathymetry and wave energy. The seaward limit of SAV beds is generally set by light availability, although a decrease in turbidity may favor more extensive SAV beds in the future (see case study).



Rocky intertidal organisms will experience effects from both the bay and the baylands.

In the latter half of this century, salinity could penetrate farther and more persistently into the estuary during the dry season, depending on several factors: how much the spring–summer runoff declines; whether and how structures and operations of Central Valley water projects are altered to supply sufficient water for human use in summer; whether tidal areas expand due to restoration and levee failures; and how much the sea level rises. Higher average salinity could allow eelgrass, native oysters, and other salt-tolerant benthic or marsh organisms to colonize farther up the estuary.

Winter salinity patterns may be more variable between and within years if storms become more intense, but such changes are difficult to project and would be altered by levee failures in the delta. In years of high outflow, or during a storm event such as that described in scenario 5, eelgrass and possibly other saline-dwelling organisms may undergo temporary diebacks during winter. The resulting shifts in distribution would affect the baylands' sediment-trapping capacity. Such storm events might also set up conditions favorable to invasive species, as may have been the case with the overbite clam (see the plankton case study).

A winter flood or an earthquake could also have lasting consequences if many levees fail in the delta or Suisun Marsh and are not repaired. This situation seems likely only if repairs take considerable time and are not feasible for all levees. Over a century, these events have a high probability of occurring, but the probability and nature of a permanent response in estuarine organisms is highly uncertain.

EFFECTS OF WARMER WATER

Rising water temperature may have a number of effects on estuarine organisms. Warmer water may stimulate a greater incidence of disease and parasite attacks. Blooms of the freshwater microalga *Microcystis* occur in the delta during warm, dry summers and may persist longer with warming. High summer air temperatures, stronger winds, and a greater tidal range may increase the risk of desiccation in intertidal areas (see the rocky intertidal organisms case study). Temperature changes may put organisms out of phase seasonally with their food or predators.

A few species may already be near their upper thermal limits, and higher temperatures are likely to prove harmful. In particular, high summer temperatures in the delta will add to the problems already besetting delta smelt. High water temperatures in Central Valley streams, particularly in combination with low flows in the dry season and a limited cold-water pool in the reservoirs, are likely to limit the viability of some salmon runs, notably winter-run Chinook (see the salmon case study). The loss, or reduction in abundance, of salmon in the estuary during the outmigration period may have ecological effects on the Bay Connection, but these cannot be predicted.

EFFECTS OF CHANGES IN SPECIES COMPOSITION

The particular species present in the bay and their relative abundance (or species composition) are likely to change in ways that influence the Bay Connection (see all case studies), but the effect of such changes is unpredictable. These changes can arise through new introductions, range expansions or contractions, habitat changes, and ecological interactions.



Changes in temperature, chemistry, and species within the open bay will affect the baylands.

Examples from the past indicate that the effects of these changes, though unpredictable, can be significant. The introduction of the overbite clam precipitated a series of events that severely altered food webs in the estuary, including a decrease in phytoplankton production and a substantial contraction of the salinity range of the northern anchovy, which had been the most abundant fish as far up-estuary as Suisun Bay (see the plankton and anchovy case studies). The resulting decreases in the spring–summer abundance of several species of copepod and mysid vastly reduced their availability as food for fish, which probably caused a decline in abundance of longfin smelt and striped bass. The Brazilian waterweed, which spread through the delta in the 1990s, provided cover for a host of nonnative fishes, while excluding native fish and native SAV, also significantly affecting the estuarine food web.

Future introductions are likely to have effects of similar magnitude. It is difficult to anticipate what species might arrive in the estuary, although the arrival of quagga and zebra mussels appears inevitable. While these freshwater mussels are unlikely to become very abundant in the bay, their grazing on delta phytoplankton could have substantial effects. Under present conditions the delta subsidizes phytoplankton in Suisun Bay, so a loss of productivity in the delta could affect that bay (see the plankton case study).

SUMMARY OF CONSEQUENCES FOR THE BAY CONNECTION

Overall some species will be extirpated, some will decrease in abundance, others will increase, others will change seasonal patterns, and still others will extend their ranges into the estuary and become established. The outcome will be an unpredictable shift in the composition of, and interactions among, estuarine organisms, which will change the suite of open-water species available for interactions within marshes.

Presumably, some marine species will be able to penetrate farther into the estuary and become significant members of the marsh fauna and flora in areas where they are not now abundant.

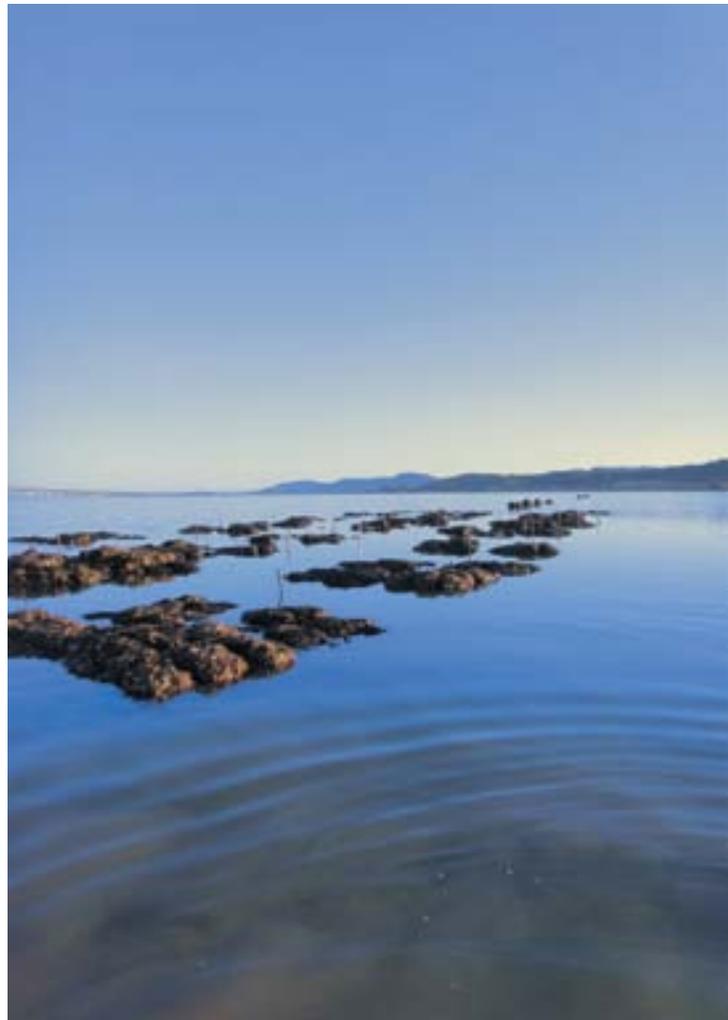
Considerations for Actions Related to the Bay Connection

The complexity of interactions in the Bay Connection makes planning for future change difficult. Addressing some critical unknowns would help reduce the amount of uncertainty around how the Bay Connection will change and what management actions should be taken. Specific characteristics of the exchange between marshes and open waters are key to understanding the Bay Connection but are poorly understood. Many aspects of the estuarine food web are not monitored, particularly the benthic communities in the Central and South Bays, as well as metrics pertaining to jellyfish and plankton. Wetlands managers can and should plan for invasions by new species. It is critical to establish a program to anticipate and prepare for the consequences of the impending invasion by quagga and zebra mussels. Another important preparation action is to finalize and implement the draft rapid-response plan in the California Department of Fish and Wildlife's Aquatic Invasive Species Management Plan from 2008 and expand it to include more estuarine species.

INTEGRATED SUBTIDAL HABITAT RESTORATION

The Bay Connection offers opportunities to adapt habitats using new configurations of subtidal and low intertidal elements. As discussed above, restoring complete tidal wetland systems, including subtidal habitats like eelgrass and oyster beds, is important for promoting resilience, given the strong links among the physical and biological processes relating to the exchange of water, sediment, organic matter, and organisms. Such integrated restoration projects provide ecological benefits, physical protection for the more landward habitats and infrastructure, and probable cost savings over equivalent isolated restoration projects.

Living shorelines restoration techniques hold promise for helping restore complete tidal wetland systems.





Native oysters provide important water quality, shoreline protection, and habitat benefits.

Subtidal habitats that increase bottom friction, mainly oyster reefs and eelgrass beds, could be placed to attenuate wind waves and thereby buffer tidal wetlands and creek mouths from erosion. Eelgrass beds offshore from a marsh may also provide food resources for waterbirds, substrate for herring eggs, and habitat corridors for fish moving between the bay and the baylands. The combination of marsh restoration and nearby subtidal habitat restoration could create local zones of sediment retention, minimizing the need for ongoing intervention. Local concentrations of oysters on constructed reefs may increase water clarity, thereby increasing the amount of light available to nearby eelgrass beds. Integrated restoration also reduces the effects of habitat fragmentation.

Restoration techniques for subtidal habitats are less understood than those for baylands, creating a need for pilot projects that address key science questions and generate data on restoration outcomes. Integrated experimental projects incorporating baylands and subtidal restoration with both constructed and natural elements should be implemented soon to generate knowledge about these new techniques as early as possible. Integrated physical and biological goals can be better incorporated into innovative designs that enhance and reinforce the ecosystem functions and services in the Bay Connection. Integrated designs can be more cost effective by providing habitat restoration benefits while testing new approaches to climate-change adaptation.

CONNECTIONS TO THE WATERSHEDS: THE ESTUARINE–TERRESTRIAL TRANSITION ZONE

Life in the Bay Area is concentrated along the bay shore. The edge of the bay is packed with ecological, economic, and cultural values. In the most urbanized areas, almost nothing is left of the natural shore, which has been fitted with major infrastructure for communications and power transmission, and for moving people, commercial goods, water, fuel, and wastes. This infrastructure rings the bay, crossing through current and former tidal marshes, crossing over and channelizing its rivers and streams, and restricting connections between the bay and its local watersheds. Much of the wildlife, water, and sediment from the surrounding hills and valleys now moves along unnatural channels and pathways through built environments to reach the bay.

Efforts to address the ecological and economic threats imposed by sea-level rise and other aspects of climate change have begun to focus on the estuarine–terrestrial transition zone (between the baylands and local watersheds), hereafter called the

transition zone. Transition zone design and management can help mitigate these threats. The transition zone can provide space for the bay to expand without creating unacceptable flood hazards and without losing the ecosystem services of the baylands. Many historical and cultural resources are associated with the transition zone, and it affords important recreational opportunities. The transition zone provides critical support for wildlife throughout the region, while also supporting its own unique plant and animal communities.

Interest in the transition zone has intensified since the Goals Project was completed in 1999. While the need to restore and conserve the transition zone was generally appreciated in the Goals Project, the broad range of transition zone services was not as well understood, and the need for a transition zone to mitigate the threats of a rising bay did not seem urgent. This Science Update presents an opportunity to address more fully the need to restore and protect the transition zone now and into the future. Hence, this report includes a definition and detailed description of the transition zone and its ecosystem services, information that was provided for the other baylands habitat types in the Goals Project. The following discussion builds on detailed information found in Science Foundation chapter 4.

Definition and Description of the Transition Zone

The transition zone is defined as the area of existing and predicted future interactions among tidal and terrestrial or fluvial processes that result in mosaics of habitat types, assemblages of plant and animal species, and sets of ecosystem services that are distinct from those of adjoining estuarine, riverine, or terrestrial ecosystems.

Mudflat at sunset



Transition zones extend along the tidal reaches of streams.



The transition zone is an integral part of a complete tidal wetlands system, but the transition zone as defined here does not include all the baylands. It does not include all of the tidal marshlands. The transition zone includes the areas of intertidal vegetation that are measurably influenced by terrestrial runoff and other freshwater discharges. It includes diked baylands that serve to store terrestrial floodwaters or that represent future space for baylands migration, since these are transition zone services, but it does not necessarily include other diked baylands.

The transition zone has often been visualized as the area of transition between tidal marsh vegetation and terrestrial vegetation. Such transitions are certainly part of the transition zone (see Science Foundation appendix 4.3). However, the full suite of transition zone ecosystem services indicates that the transition zone can be much broader in some settings. The relationships among topography, land use, runoff, transition zone services, and transition zone width can be represented by a simple transition zone classification system (see Types of Transition Zones). There is also a relationship between transition zone type and approaches to transition zone planning and management. These and other relationships are explained in this section to support the recommended transition zone conservation actions.

The transition zone provides a physical and ecological connection between the baylands and local watersheds. It connects the bay to both its developed and its undeveloped margins. It extends all along the bayshore and along the tidal reaches of rivers and streams. The transition zone extends landward (across wetlands and uplands, and along streams and rivers) to the limits of tidal effects on terrestrial and fluvial conditions. It extends bayward (across marshes and sloughs) to the limits of the effects of terrestrial runoff and other freshwater discharges on conditions of the baylands.

The transition zone varies in width from place to place and over time. In the landward direction, its width is affected by the vertical range of the tide, the slope of the land, and the locations of built structures that control the upstream or landward movement of tidal water. In the bayward direction, its width depends

Figure 20 Transition zone boundaries corresponding to different ecosystem services, showing (A) the upper and lower boundaries based on plant species assemblages indicative of the landward marsh edge, plus the landward boundary of the high-tide refuge service for the transition zone associated with a levee (Richmond, Contra Costa County); and (B) these same kinds of boundaries plus the range in head of tide and the landward limit of the flood-control service for the transition zone associated with a perennial stream (San Antonio Creek, Sonoma County). The area of stream flooding in (B) relates to a railroad grade that constricts the connection between the fluvial and intertidal portions of the floodplain. (Note: The boundaries in this figure are provided as examples for the purpose of illustration and are not based on field measurement or quantitative modeling.)



Key	
	Landward limit based on vegetation
	Bayward limit based on vegetation
	Landward limit of refuge from high tides
	Landward limit of stream flooding

on the volume of terrestrial runoff entering the baylands. In general, for any given volume of runoff, the transition zone is wider where the tidal range is greater and where the land slopes gently to the bayshore. It is narrower where the tidal range is smaller and the land is steeper.

The required width of the transition zone also varies depending on the desired ecosystem services (fig. 20). For example, a broader transition zone is needed to provide refuge from high tide for marsh wildlife than if such refuge is not provided, and a broader zone is needed to accommodate sea-level rise for the next century than for the next half-century. Field and map indicators can be used to estimate the maximum width of the transition zone present or needed at any location around the bay.

The principal indicators of the landward extent of the transition zone are

- ◆ the upper extent of tidal marsh vegetation
- ◆ the area of high-water refuge for marsh wildlife (from both tidal and fluvial flooding)
- ◆ the head of tide, which is the upstream limit of the influences of tidal waters on channel geomorphology and hydraulics

- ◆ specific, complex habitat mosaics created by large-scale interactions among tidal, fluvial, and terrestrial processes
- ◆ migration space for sea-level rise
- ◆ ecological connectivity for wildlife, including fish and invertebrates, that use baylands and adjacent terrestrial or fluvial habitats

The principal indicators of the bayward extent of the transition zone are:

- ◆ the bayward extent of processes originating at the back of the marsh
- ◆ the extent of influence from freshwater discharge

Examples of the first indicator include seasonal freshwater seeps and shallow pans from natural drainage processes (or a lack thereof), the wrack line, and the extent to which pets and people venture into the marsh from levees and paths. For the second indicator, freshwater discharge includes terrestrial runoff that reaches the transition zone through rivers, streams, canals, ditches, and effluent from water treatment facilities. The effects of freshwater discharge can be assessed as the bayward extent of tidal marsh plant species that are indicative of fresh or brackish water conditions, and the bayward extent of fluvial bedload (the sediment transported along the bed of a stream rather than suspended in the water column). The bayward effects

P E R S P E C T I V E S F R O M T H E S T E E R I N G C O M M I T T E E

Box 6 The Future Shoreline

The bay shoreline is a desirable address. Homes, businesses, institutions, airports, seaports, and myriad others all derive some benefit from their shoreline location, and some must be there. Airports can reduce noise impacts to their neighbors and increase public safety by conducting flight operations over the bay. Restaurant patrons, homeowners, office workers, and others enjoy fantastic bay views and often have ready access to the Bay Trail, waterfront parks, or other recreational opportunities. Marinas, seaports, fishing piers, and other water-dependent facilities require a bayside address. Shoreline development contributes significantly to the character of

the region, providing places for memorable events that help make the Bay Area such a special place.

Some developed landforms slope up steeply from the shoreline, others meet the shoreline with hardened structures, and some are level or gently sloping. Riprap revetments, sea walls, and levees provide structural protection from flooding or erosion, sometimes in conjunction with shoreline wetlands. Where shorelines are steep, like those in parts of Marin County, San Francisco, or the Carquinez Strait, wetlands will not be able to form or migrate as the sea level rises. Where land slopes gently up from the shoreline, wetlands can migrate inland, though in many

places only if barriers are removed to allow wetland formation, or if adjacent land uses are changed.

As the Bay Area develops strategies to adapt to sea-level rise, it will face hard choices in selecting the developed areas it will protect, areas where the public benefits of allowing the bay to migrate inland outweigh the cost of protecting the current shoreline, and areas where wetlands can be restored or managed in place. The transition zone research and analysis recommended by this Science Update can inform the complex process of adapting to a changing bay in an ecologically sound and forward-thinking manner.



Above: Transitions are evident even in urbanized baylands.

Right: Black-necked stilt at restored wetland



of freshwater discharge can include the extension of fluvial levees into tidal marshes (fig. 16), the deposition of sediments on marshes that adjoin streams (fig. 17), and the existence of brackish marsh vegetation.

Transition Zone Ecosystem Services

The ecosystem services of the transition zone relate strongly to its role in linking the baylands to local watershed processes. Inorganic sediment derived from local watersheds helps form and sustain tidal marshes. Freshwater runoff from local watersheds creates salinity gradients through the baylands that greatly increase the biodiversity of the region. Many wildlife species, including birds of prey and salmon, move between the bay and local watersheds through the baylands. The bay and its local watersheds are linked together by the baylands, and the mechanisms of this linkage are the workings of the transition zone.

The transition zone delivers the following major ecosystem services:

- ◆ buffering for the landward effects of tidal processes and the bayward effects of fluvial and terrestrial processes, which helps control pollution, biological invasions, and erosion
- ◆ flood protection where channels, floodplains, and floodwater storage areas exist
- ◆ sea-level rise migration space for the baylands, especially for tidal marsh and the tidal reaches of rivers and streams
- ◆ nutrient processing in transition zone wetlands
- ◆ groundwater recharge during floods in riverine floodplains and stormwater retention basins that are part of the transition zone
- ◆ support of diverse native wildlife (including fish) through the provision of
 - habitat for transition zone species, including important pollinators for marsh plants and invertebrate prey for marsh fauna
 - refuge from predators and physical stressors like high water
 - foraging areas

- ▷ movement corridors along the shore or up into watersheds (especially important for allowing certain species to find the right salinity in variable conditions)
- ▷ landscape complexity by increasing the number of habitats and combinations of adjacent habitats
- ▷ a wide range of conditions that promote the physiological, behavioral, and other adaptations necessary for population persistence
- ◆ cultural amenities, including recreation and educational activities
- ◆ carbon sequestration

More details on these services and the species of management concern that the transition zone supports are given in Science Foundation chapter 4.

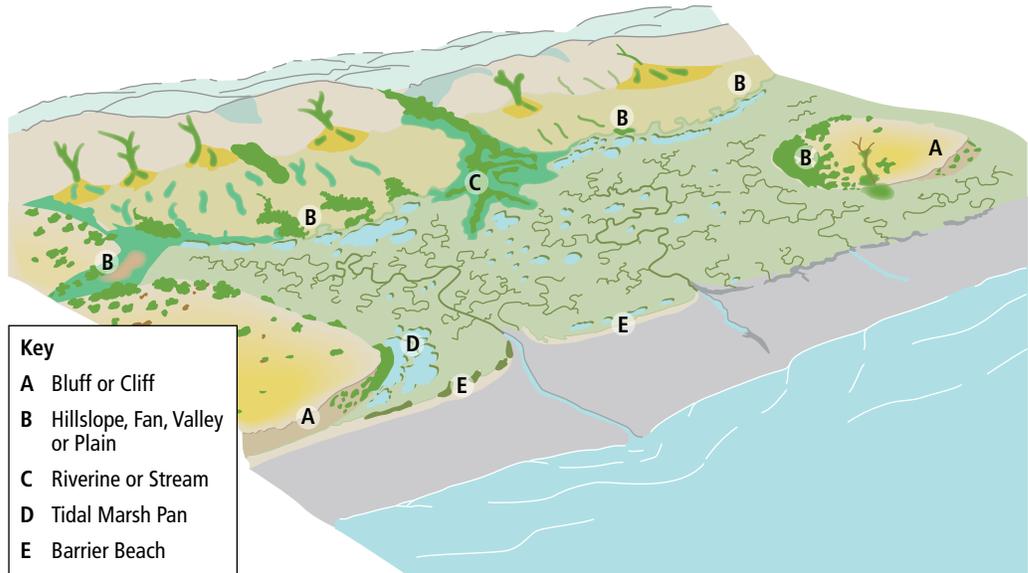
Types of Transition Zones

The transition zone typology has two parts. One part organizes the transition zone into types based on formative processes and physical structures (fig. 21). The second part organizes the transition zone into subzones based on the spatial limits of their ecosystem services. Seven types of transition zones represent the full range of historical and existing transition zone conditions for the bay (fig. 21 and 22). Each type of transition zone consists of two to four subzones that provide different suites of services. Subzone 2 has been the focus of recent marsh–upland transition zone restoration efforts and is highlighted in Science Foundation appendix 4.3.

The stratification of the transition zone into a number of contiguous subzones based on the “footprints” of its various services has precedent in riparian buffers. Many public agencies responsible for riparian buffers subdivide them into three or more component zones that correspond to different kinds or levels of buffering. From the perspective of riparian science, the transition zone as defined here is essentially the riparian zone of the bay.

Transition zone subzones extend varying distances inland.





- Key**
- A Bluff or Cliff
 - B Hillslope, Fan, Valley or Plain
 - C Riverine or Stream
 - D Tidal Marsh Pan
 - E Barrier Beach

Figure 21 A typical arrangement of the natural transition zone types in a virtual San Francisco Bay landscape. The tidal salinity regime can be brackish or saline. Natural salt pond and artificial levee transition zone types are not included in this figure.

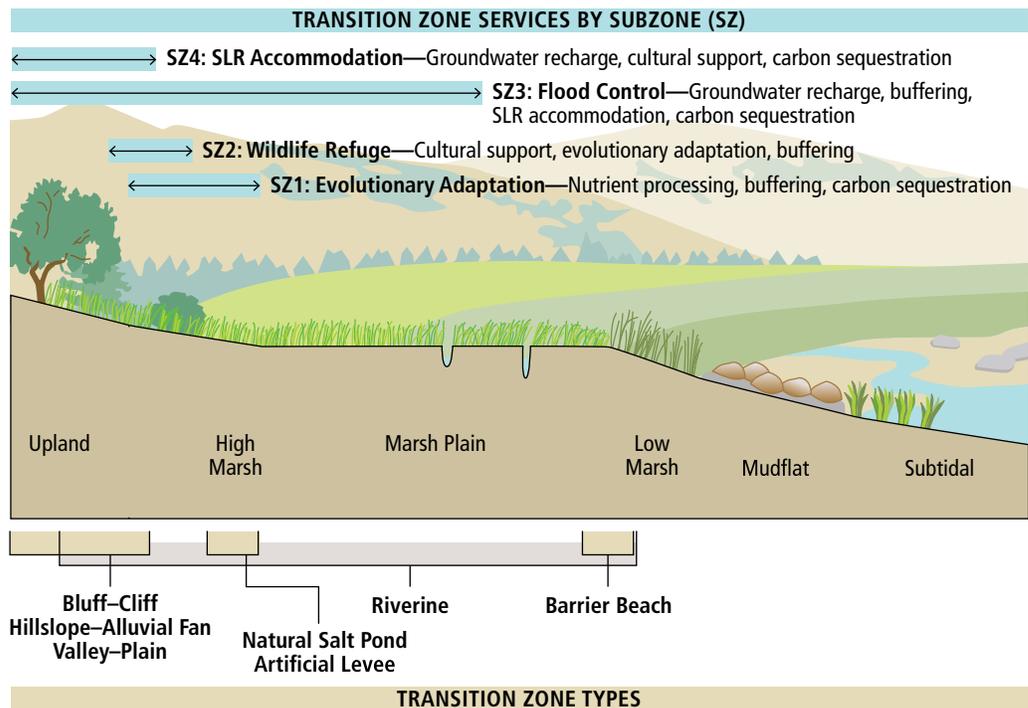


Figure 22 Spatial relationships among transition zone types and subzones. Subzones 3 and 4 extend landward of the upland extent shown in this figure. The riverine type extends bayward to the limits of the effects of freshwater discharge on intertidal vegetation. The primary services of each subzone are shown in bold. Services common to all transition zone types, such as wildlife movement and landscape complexity, are not shown.

One type of transition zone, the *barrier beach*, often occurs at the bayward margin of tidal marsh. It is identified as a type of transition zone because it provides many of the ecosystem services as the other transition zone types. For example, barrier beaches can serve as a high-tide refuge, and they support the evolutionary adaptation and movement of intertidal plants and animals.

The typology can serve to guide transition zone restoration and management. For example, successful restoration will require knowing what type of transition zone is best suited for a given restoration site, based on the local controlling factors and processes. Mismatches between transition zone types and settings may cause restoration efforts to fail. The kinds and levels of service provided by the transition zone can be controlled to some degree through the design and management of subzones.

Considerations for Actions Related to the Transition Zone

FUTURE CHANGES IN THE TRANSITION ZONE

The transition zone will be affected by the impacts of climate change on local watersheds as well as sea-level rise. The projected increase in the intensity of rainstorms could result in more erosion of hillsides and streams, which in turn could increase the volumes of sediment delivered to the hillslope–alluvial fan, bluff, and riverine transition zone types. The projected rise in dry-season air temperatures and the possibility of longer droughts could result in more frequent disturbance by fires in the undeveloped landward subzones of each transition zone type. It's very difficult to predict how the terrestrial vegetation of the transition zone will be affected by climate change, but invasions of nonnative plant species are likely to increase, given that these species tend to exploit disturbed environments. Changes in the plant community of the transition zone will in turn lead to changes in how the transition zone supports wildlife.

The basic effects of a rising bay on transition zone conditions are perhaps more predictable. As the bay rises, the transition zone will tend to migrate landward if there is adequate migration space. In many areas, providing adequate space would

Development backs many of the region's existing marshes, limiting transition zone services and opportunities.





Waterways will provide opportunities for transition zones to move inland, where constrictions allow.

require relinquishing some human activities located landward of existing marshes or transition zones. Otherwise the transition zone will be increasingly compressed or will drown. Since the diversity of services of the transition zone increases with the number of intact subzones, and since the levels of service of any subzone tend to increase with its width, compression of the transition zone will likely result in a loss of both the diversity and levels of its services. This highlights the importance of a broad subzone 4 that can accommodate the landward migration of all the subzones.

Extreme weather events can significantly affect conditions of the transition zone. Extreme storm events that cause water to overtop roads, levees, tide gates, and other structures can suddenly alter the transition zone by changing soil and moisture conditions, which will affect plant and animal distributions and survival. As the head of tide migrates upstream with sea-level rise, the likelihood increases that wind-generated waves, boat wakes, and extreme high tides, including “king tides,” will overtop levees and berms. Such extreme high events are likely to affect conditions in the transition zone as much as, or more than, the increase in the average bay height.

Under natural conditions, the transition zone can be resilient to climate change and extreme weather. For example, estuarine barrier beaches can naturally gain height with the deposition of materials during a storm wave run-up, and alluvial fan vegetation buried by episodic riverine flood sedimentation can regenerate after a few years. This does not mean that the ecosystem services of the transition zone will



Many native species depend on transition zone services.

withstand climate change and sea-level rise without human intervention, but rather that understanding transition zone processes allows careful intervention to sustain appreciable levels of services.

If nothing is done to protect and restore the transition zone, the diversity and magnitude of the ecosystem services it provides will decline. The primary reasons for this are the lack of migration space, the transition zone's greater vulnerability to erosion and disturbance as the adjoining tidal marsh erodes, a greater vulnerability to biological invasion due to increased frequency and magnitudes of disturbance, and fragmentation along the bayshore due to its extreme compression against the built environment.

The response to future change will vary by the type of transition zone. Management plans need to take into account both the type of transition zone and the desired ecosystem services. Detailed discussions for each transition zone type are provided in chapter 4. Key points that relate to management actions for particular types of transition zone are summarized here.

For steep transition zones on constructed levees, the "horizontal levee" is a recent concept for building habitat resilience and enhancing ecosystem services. The traditional levee is augmented with carefully graded fill that extends the transition zone bayward to create a wide, low-gradient terrestrial slope. Diked wetlands can be designed into the horizontal levee. For example, reclaimed wastewater effluent could be used to irrigate the slope to create freshwater for brackish wetlands. The concept is most applicable to urbanized areas that lack migration space. Implementation might require partially filling diked baylands or shallow subtidal areas adjacent to the existing transition zone. A complementary strategy is to realign

the flood-risk-management levee to a new location further inland (as described in Projected Evolution of Baylands Habitats and fig. 18).

For alluvial fan and valley plain transition zones, the projected increase in rainstorm intensity and riverine flooding could be used to increase the supply of sediment through the fans and valleys and to the marsh, pushing the transition zone bayward and enlarging baylands migration space, as well helping the marsh keep pace with sea-level rise. This approach would be effective where fluvial fans and valleys have not been developed. At the same time, the projected increase in air temperatures during the dry season and increased intensity of droughts could decrease surface and groundwater flow through the alluvial fans and valleys. This decrease in flows could reduce or eliminate the slope and depressional wetlands, along with the brackish marsh, which are naturally associated with this transition zone type. Creative ways to improve safe yields of sediment and to assure adequate flows of clean water through the fans and valleys that adjoin the bay are needed to protect and restore the valley–fan transition zone. In short, wide and gently sloping transition zones will last longer if connected to active estuarine and terrestrial processes.

To prevent increased riverine and tidal flooding associated with more intense storm events and higher sea level, levees in many places will need to be raised and extended upstream, or development moved back, to make room for riverine and tidal influences. Alternatives to longer and higher levees should be considered where possible. For example, the restoration or construction of terrestrial floodplains should be considered, as should the ability to shunt floodwaters across tidal marsh plains during low tide and into diked baylands during high tide. In some areas, it might be possible to move riverine levees farther apart, to make room for floodplains between the levees. Flood control designs can be integrated with the realignment of infrastructure



Alternatives to longer and higher levees should be considered where possible.

and a planned retreat of land uses at the landscape scale to create migration spaces with abundant riverine ecosystem services. These concepts and others could be integral elements of landscape designs that reconnect the bay to its local watersheds in ways that restore the ecosystem services of the baylands as a whole.

Future policies concerning watershed-based sediment management and flood control will largely determine whether flooding is used to nurture the transition zone and the rest of the baylands. Watershed-based sediment management, as envisioned for rivers and streams impaired by fine sediment, should consider the effects of sediment management on the riverine transition zone and other components of the baylands.

TRANSITION ZONE DESIGN AND MANAGEMENT

Managing the transition zone presents difficult challenges because of the need to balance demands for ecosystem services against existing development. Meeting these challenges requires ongoing coordination among agencies at all levels of government. However, the conflicts among transition zone management objectives can be mitigated through transition zone design. At this early stage of transition zone restoration science and engineering, pilot projects are needed to test various design concepts. In general, each restoration project should set ecosystem service goals for the transition zone type that best fits the restoration site. These goals should be based on an operational understanding of the formative processes, local constraints, and future opportunities for further restoration.

Currently, there is no regional map of the transition zone as defined here. A regional transition zone mapping effort is needed to identify and track restoration opportunities, to assess the relative effects of restoration and ambient climate change, and to evaluate the efficacy of state and federal policies for protecting the zone. Local maps are needed to inform restoration design. The optimal mapping approach will probably involve estimating the extent of each type of transition zone and the width of the subzones, such that the map can inform the restoration and management of specific ecosystem services.

RISKS FROM FUTURE CHANGE FOR WILDLIFE

Wildlife, here defined to include both animals and plants, has evolved in the San Francisco Estuary to accommodate environmental change. Local extinction and colonization of new habitat have occurred repeatedly. In the present day, however, wildlife faces the cumulative anthropogenic impacts of (1) habitat loss, fragmentation, and degradation; (2) barriers to dispersal, such as freeways and cities; (3) contaminants; and (4) the alteration of habitat and food webs by nonnative species. Moreover, the unprecedented rate of climate change anticipated in the coming decades will exacerbate these stressors. The combination of higher rates of change, more intense extreme events, and additional stressors poses a high risk to wildlife.

These risks to wildlife can affect long-term population trends and the population viability or sustainability of baylands plants and animals. Population trends depend on the rates of survival, reproductive success, recruitment, and dispersal. Population

viability depends in good part on population resilience, or how well species tolerate or recover from changes in the environment.

The exact consequences of climate change for wild plants and animals cannot be predicted with certainty. Nevertheless, there is enough information about changes in habitat and climate to foresee the likely general trends and provide recommendations for management actions to prepare for and alter those trends. Here we consider the short- and long-term impacts of the five future scenarios (see section Future Scenarios Evaluated) on wildlife, building on detailed information found in Science Foundation chapter 5.

Case Studies

The Science Foundation chapter on wildlife (chapter 5) and this summary of it are based on 32 case studies covering a wide variety of plants and animals (table 1). These case studies are located in Science Foundation appendices 3.1 and 5.1 and describe the effects of drivers on populations, guilds, or communities. The wildlife workgroup used five criteria to select focal groups for case studies. Primary criteria for the focal taxa were

- ◆ well-understood ecological processes and population status
- ◆ high conservation concern or the group's marked vulnerability to climate change
- ◆ qualities representative of other species

Secondary criteria were

- ◆ a particular association with baylands habitat
- ◆ the group's important ecological role (for example, as a key player in the food web)

Using patterns of impacts apparent from the case studies, we recommend management actions to enhance population resilience and thereby maintain or restore the health of wildlife populations. These case studies update the Species and Community Profiles published for the Goals Project by considering (1) the likely impacts of future change, (2) other new information learned since 1999, and (3) specific management recommendations relevant to (1) and (2).

American white pelicans rest on a protected island within a managed pond.



Table 1 List of case studies (available online in Science Foundation appendices 3.1 and 5.1)

Species	Indicator for	Habitat	Status in Baylands
Mammals			
salt marsh harvest mouse	marsh (tidal and non-tidal) small mammal	tidal marsh; diked bayland	resident in baylands
Suisun shrew, salt marsh wandering shrew	marsh (tidal and non-tidal) small mammal	tidal marsh; diked bayland	resident in baylands
river otter	aquatic mammal (creeks and rivers)	creeks and rivers	mostly terrestrial–bayland interface
harbor seal	aquatic mammal, using bay and mudflat	open bay, mudflat, sandbar, rocky intertidal	resident in baylands
Marsh Birds			
Ridgway’s rail	tidal-marsh-dependent birds	tidal marsh	resident in baylands
song sparrow	tidal-marsh-dependent birds	tidal marsh	resident in baylands
black rail	tidal-marsh-dependent birds	tidal marsh	resident in baylands
northern harrier	marsh predator	multihabitat	resident, multihabitat
Waterbirds			
American avocet, western sandpiper	avocet: large shorebirds sandpiper: small shorebirds	marsh; mudflats; managed pond	avocet: breeder in baylands sandpiper: migrant
least tern and Forster’s tern	fish-eating birds	beaches, marshes, sloughs, islands	breeder in baylands
dabbling ducks: northern shoveler, northern pintail, American wigeon, gadwall, mallard, green-winged teal	six species of dabbling ducks	diked bayland and tidal marsh; managed ponds	both resident and migratory species
diving ducks: scaup (lesser and greater), surf scoter, bufflehead, canvasback, ruddy duck	bay ducks; sea ducks; stiff-tailed ducks	diked bayland; open water; managed ponds	predominantly migrant



Least sandpiper

Amphibians			
California toad	wetland amphibians	wetlands	resident
California red-legged frog	wetland amphibians	wetlands	resident
Fish			
Pacific herring	subtidal	shallow aquatic	migrant
delta smelt	upstream part of estuary	open water	migrant
longfin smelt	pelagic throughout estuary	open water	migrant
longjaw mudsucker	marsh fish	pickleweed marsh	migrant
tidewater goby	small estuaries	estuarine lagoon	breeder
grunion	recovered native	sandy beach	breeder
chinook salmon and steelhead	migratory fish	vegetated marsh edge	migrant
Invertebrates			
macroinvertebrate: Dungeness crab	aquatic: nursery value of baylands	shallow aquatic, eelgrass	migrant
terrestrial marsh invertebrates	multiple species	tidal marsh	resident
Vernal Pool Community			
plants, crustaceans, other invertebrates, plants	multiple taxa	freshwater, ephemeral pools	resident
Plants			
invasive and native Spartina	invasive and native Spartina	tidal marsh	resident
submersed aquatic vegetation	multiple species	open water	resident
low tidal marsh graminoids	multiple species	tidal marsh	resident
high tidal marsh annual forbs and graminoids	multiple species	tidal marsh	resident
high tidal marsh subshrubs and perennial forbs	spring high-tide zone	tidal marsh	resident
high tidal marsh perennial graminoids	spring high-tide zone	tidal marsh	resident
terrestrial ecotone/high-marsh graminoids	multiple species	terrestrial transition zone	resident
terrestrial ecotone psammophyte	multiple species	terrestrial transition zone	resident

Impacts on Wildlife

Two types of impacts from future change will affect wildlife: long-term trends and episodic events, each of which relates to particular drivers (see Science Foundation chapter 5 for the particulars of this conceptual model). Long-term trends will affect the average population sizes through changes in habitat quantity and other habitat characteristics, especially structure and salinity. However, the average population

size through time is not the best indicator of population viability or sustainability, as extinction risk is particularly exacerbated by extreme events, floods, droughts, and storms. Such risk is amplified in smaller, isolated populations that result from habitat loss and fragmentation, so the two types of impacts interact.

IMPACTS ON SURVIVAL AND GROWTH

From Inundation and Salinity

Northern harrier



Increased inundation and higher salinity will change the distribution of plant communities with far-reaching effects for wild animals and the plants themselves. As the sea level rises, the distribution and abundance of submerged aquatic vegetation adapted to deeper flooding is expected to increase. Inundation and salinity limit the populations of many brackish plants. For example, the effects of salinity and inundation stress due to sea-level rise will reduce the first-order tidal-channel habitat supporting the rare Suisun thistle and thus limit its distribution and abundance throughout Suisun Marsh.

Marshes that are now brackish will shift to salt marsh vegetation, and brackish marsh communities will extend into formerly freshwater marsh areas. Tidal marsh bird communities will probably shift in keeping with the plant assemblages. Change in the distribution of brackish bulrush and tule will likely cause change in the distribution and possibly the population size of birds, such as marsh wrens and common yellowthroats, that rely on these plants for cover and breeding sites. Storm events causing a onetime deposition of seawater to high elevations can leave a legacy of saline soil, and heavy deposits of wrack can smother vegetation.

Fish communities will also shift with salinity and inundation changes. Freshwater fish that are currently found in Suisun Marsh will become rare. On the other hand marine fish, including halibut, flounders, and white seabass, are likely to become more reliable components of the fish community of the Central Bay. With longer inundation periods, aquatic species associated with higher salinity marshes, like longjaw mudsuckers and Dungeness crabs, may have less exposure to avian predators and longer foraging times. However, higher temperatures during the periods of exposure may override the benefits of increased inundation.

Tidal marsh birds and mammals are particularly susceptible to the effects of inundation from storm events. Flooding of the marsh has energetic consequences, because terrestrial animals cannot access marsh foods. In one example, black rails were unable to forage for many hours over several days during a winter storm. The stress on this species was not just due to the inundation, but also to its duration. The rails had to expend energy to stay warm but could not replenish themselves with food. Marsh residents, including salt marsh harvest mice, can perish during such extended flooding.

Perhaps most importantly, inundation leads to a greater risk of predation. During high-water events, terrestrial wildlife in the marsh is forced into the landward edge of the marsh or must cling to tall vegetation, concentrating it in small areas where predators can more easily take it. Thus, marsh inundation interacts with predation to affect terrestrial marsh vertebrates. This mortality pressure is well demonstrated by the Ridgway's rail, whose survival rates are lower when tides are higher.

The loss of mudflats, or a general lowering of mudflats relative to mean sea level, could lead to the decline of several waterbird groups. Deeper water in mudflats or managed ponds would reduce the foraging habitats of wading birds, shorebirds, and dabbling ducks. Shorebirds are already energetically limited during the winter and migration, so they rely on good foraging in the estuary to complete their energy budgets. Changes in salinity may also affect shorebirds by altering the distribution and abundance of their prey.

From Temperature

Warming temperatures will also affect the survival and growth of wild animals and plants. Higher temperatures may result in an energetic imbalance for some species, due to fewer foraging hours or a need to spend extra energy to maintain physiological processes. However, lower freshwater flows and higher salinities may improve the growth of salmon in the baylands. Of much greater concern are thermal stress and dewatering upstream, particularly for steelhead. Higher temperatures and CO₂ levels will affect plant growth, survival, recruitment, dispersal, and competition, as well as altering ecosystem processes, such as decomposition, nutrient cycling, primary productivity, and organic-matter accretion. The outcomes of these changes may be significant, but the complexity of the systems and the uncertainty of the changes make them impossible to predict accurately.

From Drought

Drought and the associated increases in salinity cause significant mortality in amphibians and plants. The combined effects of drought and hypersalinity will harm mid- to high-marsh plants, such as the Suisun thistle and gum plant that are adapted to brackish rather than saline conditions. The gum plant is an important resource for marsh wildlife. Drought will likely cause a mass dieback and smaller plants, which will reduce the cover and nest sites for marsh animals.

IMPACTS ON REPRODUCTIVE SUCCESS

From Inundation and Salinity

Many mid- to high-marsh plants may fail to reproduce in the absence of a low-salinity period for germination during the winter and spring. This is of greatest concern for uncommon local endemic species, such as the Suisun thistle and water hemlock, but applies to other plant species as well.

The nests of Ridgway's rails, black rails, and tidal marsh song sparrows are likely to be flooded more often from sea-level rise and extreme storms. More frequent storms could cause the failure of renesting attempts after an initial failure, resulting in complete reproductive loss for the year. Reproductive failure of this kind can rapidly lead to severe reductions in population size of these relatively short-lived species. Salt marsh harvest mice, baylands shrews, shorebirds, and other breeding waterbirds are probably also at risk for reduced reproductive success or lower offspring survival due to flooding.

Harbor seals require tidal flats and other habitat types with particular characteristics to haul out and birth pups. The loss of adequate haul-outs (as a result of erosion or drowning) is a concern, resulting in reduced reproductive success. Similarly,

shorebirds require suitable breeding locations, including beaches and mudflats, which may be lost due to sea-level rise.

From Freshwater Outflow

If reduced or earlier delta outflows occur later this century, they may reduce the reproductive success of aquatic wildlife. Many aquatic species have shown better survival or reproduction in years of higher delta outflow. Restriction of outflow events to early in the water year could restrict the spawning success of both longfin smelt and delta smelt. Prolonged summertime conditions could reduce the survival and fecundity of delta smelt in particular, if the salinities they occupy in the summer and fall were to move upstream into less productive portions of the delta. The ability of longfin smelt to use more oceanic waters should allow them to be more resilient to increasing salinity than the delta smelt. Pacific herring require a combination of solid substrates and appropriate salinity that is likely to become spatially disconnected during future climate conditions. Suitable salinities will move upstream into San Pablo Bay, where the appropriate solid substrates are rarer. Thus, herring eggs will be deposited on inappropriate substrates or in even greater densities on the limited patches of appropriate substrate, leading to less successful reproduction.

Amphibians, including the California toad and California red-legged frog, require freshwater ponds of sufficient depth and appropriate temperature. Breeding ponds need to maintain appropriate conditions long enough for offspring to mature. Climate change may result in ponds that are too salty or that dry out too quickly.

IMPACTS ON MOVEMENT AND DISPERSAL

As habitat configurations change, especially if the baylands become more fragmented, dispersal limitations that already affect many baylands species will become more important. Annual forbs of concern in the high tidal marsh include several rare or endangered species (e.g., *Chloropyron maritimum*, *C. molle*, *Castilleja ambigua*). These species have limited ability to spread or recolonize, or even maintain their number, and recruitment is also limited due to competition with nonnative species. Thus, for the native marsh species of concern to establish populations in new areas, active translocation may be required. A similar situation exists for several rare native plants from vernal pool habitats.

IMPACTS OF PREDATION

Current levels of predation are already straining the resilience of many baylands wildlife populations, especially because predators from adjoining uplands (including developed areas) can easily access the baylands via built structures like levees and utility towers. Predation may increase for a number of reasons. Nonnative and human-associated predators may gain easier access or experience a rise in population; the edge effects of baylands becoming squeezed against the shoreline may increase; or refuge may be inadequate at times of stress, such as high-water events.

Predators that are already affecting baylands wildlife populations, such as California gulls and other human-associated predators, must not become more prevalent. Increased inundation and higher sea levels are likely to enhance mosquito

production, and any resultant stocking of mosquito fish into temporary ponds could severely reduce the reproduction of California red-legged frogs and California toads. Levee enhancement and other efforts to buffer human infrastructure from the impacts of climate change are likely to improve access for predators, especially human-associated predators like raccoons, cats, dogs, and rats.

Stress to tidal marsh wildlife from high-water events is often coupled with intense predation during the flooding. Also, river otters require dense vegetation for refuge during high flows. Designing habitats that function as refugia under such extreme conditions will be an important part of planning for the impacts of climate change.

IMPACTS OF DISEASE

Risks to wildlife populations due to disease are expected to rise with climate warming. Shorter, milder winters are expected to increase the spread of disease. For both plants and animals, pathogens may evolve faster in response to climate change than host populations, thus spreading more quickly with more virulent results. Plant disease effects will likely increase from climate change. Strong plant–microbial linkages, including that of mycorrhizae, may help reduce disease, but climate-change predictions for microbes are not available. Amphibian chytridiomycosis (caused by *Batrachochytrium dendrobatidis*) is of great concern for the California toad. Some warming may cause *B. dendrobatidis* to spread or increase, but substantially higher temperatures may actually reduce the pathogen. Avian cholera infecting waterfowl is a concern in the estuary now, but future incidence of the disease has not been projected. River otters are currently subject to disease, and a reduced prey base from climate change may affect the susceptibility of otters to disease. Harbor seals may be subject to pathogen shifts through greater proximity to terrestrial carriers of morbillivirus (dogs, cats, raccoons, skunks), *Leptospira* (rats), *Toxoplasma* (felines), and *Sarcocystis* (opossums).

IMPACTS ON COMMUNITY COMPOSITION

Altered climate will likely produce new assemblages of species, thus changing the nature of interactions among species, such as competition. Climate change may cause both nonnative species to invade the baylands, and species native to California to



Pickleweed

Box 7 Regulatory Challenges and Opportunities

Given the need to proceed rapidly with baylands restoration to create resiliency to climate change, project proponents and regulatory agencies must better align their practices and reform the lengthy and complicated permit process that is required for restoration to proceed. Agencies likely to have a role in the permitting process of Bay Area wetlands projects include the US Army Corps of Engineers, the National Marine Fisheries Service, the US Fish and Wildlife Service, and the US Environmental Protection Agency at the federal level, and the San Francisco Bay Regional Water Quality Control Board, the California Department of Fish and Wildlife, the San Francisco Bay Conservation and Development Commission, and potentially the California State Lands Commission at the state and regional levels. In addition, wetlands restoration projects may need local authorization from cities or counties, and those that cross paths with railroad tracks, pipelines, highways, and utilities will need additional permissions in order to successfully protect the infrastructure. All these agencies can and often do require changes to designs or monitoring

plans to ensure that the project is in compliance with their respective laws and policies.

Current Constraints

All applicants, whether their projects are large or small, must navigate the same process, providing much of the same detailed information to the various permitting agencies, repackaged each time into agency-specific formats. Illustrating the difficulties of moving forward with restoration quickly, the South Bay Salt Pond Restoration Project began planning its permitting approach shortly after property acquisition was completed in 2003. It received permits from most of the agencies listed above between August 2008 and January 2009.

Some agencies rely on another agency to proceed with permitting actions (e.g., a federal nexus is determined through an Army Corps of Engineers 404 permit, which triggers resource agency consultations under the Endangered Species Act) or require other environmental clearances, such as those mandated by the California Environmental Quality Act. A single application (the Joint Aquatic Resources

Permit Application, or JARPA) is accepted by all the agencies listed above; however, due to its multiuse nature, it is cumbersome to complete.

On the regulatory side, agency staffing has been increasingly underfunded, leading to less-than-optimal conditions for processing permits. Lengthy permit processes have resulted in some project managers losing funding because the regulatory process extends beyond the life of some grants.

Opportunities

Monitoring is typically required by the regulatory agencies to ensure that each project is meeting its goals and the agencies' requirements. These agency monitoring requirements do not always directly address the scientific uncertainties facing a specific project. A coordinated, regional monitoring program should be created that uses this required data gathering to (1) support the establishment of streamlined permitting mechanisms for restoration projects (e.g., through regional general permits), (2) ensure that the project is not having a negative impact on resources, and (3)

move into the estuary. Conversely, current species may be extirpated from the estuary. The consequences of these new assemblages are not known, but the population viability of native wildlife may be reduced. For example, warmer temperatures and reduced circulation combine to produce lower dissolved oxygen levels, which promote the spread of predatory snails that can decimate native oysters. As another example, the introduction of various Asian gobies that prey upon and compete with tidewater gobies may preclude the reestablishment of tidewater gobies into their former areas. More studies are needed to identify the pathways by which a change in community

inform restoration design and management practices regionwide.

Regional mapping efforts pursued at a scale and with detail sufficient for an analysis of existing aquatic resources (quantity and quality) and of potential restoration sites could provide regulatory agencies with a more solid foundation for priority-based decision making. A plan for regional monitoring is incorporated in the state's Wetland and Riparian Monitoring Program (WRAMP), which produces regular reports on trends in wetland extent and condition and relates these trends to management actions, climate change, and other natural and anthropogenic factors in a way that informs future decisions and recognizes habitat differences in the bay's various sub-embayments.

A revised permit process should therefore include the production of a coordinated monitoring data set to inform future projects, along with built-in flexibility with regard to the number of sites that would require monitoring. Under such a permitting scheme, regulatory agencies would be able to establish a stratified sampling protocol such that each site would not necessarily need to be monitored every year. Additional flexibility

could be written into the program to allow the adaptive management of sites and to give permittees the ability to truly experiment, so that a failure to meet performance standards will not necessarily entail habitat replacement where valuable learning has occurred. This flexibility may require a greater tolerance for risk from short-term impacts in the interest of testing restoration concepts intended to provide more resilient systems in the long term.

Upcoming Challenges

Managing sediment on a watershed scale is an emerging challenge. Innovations and varied approaches to the existing restoration process and regulatory frameworks will likely be necessary in order to facilitate the availability of sediment where it is needed to sustain tidal marshes. A high-priority example of this is the redesign of flood-control channels to allow for natural processes to move sediment from channels (where it impedes capacity) to the baylands (where it is needed). How we take full advantage of other sources of sediment in the system, such as navigational dredging projects, will be critical to address as well.

Another example of an emerging challenge is potential reliance on

baylands restoration projects to mitigate greenhouse-gas emissions. Baylands restoration projects that are designed to maximize carbon sequestration may not fully meet other habitat objectives that regulatory agencies are charged with advancing.

Projects will increasingly need to meet multiple objectives, including climate mitigation, flood control, shoreline protection, and habitat enhancement. Addressing such challenges will require a comprehensive analysis of the specific challenges paired with an understanding of the distinctions among agency historical practices (cultural norms), internal agency guidelines, enforceable policies, and laws and regulations. Certain regulatory challenges may be resolved on a shorter time frame through modifications within the existing regulatory frameworks. Other challenges may require a longer-term process that includes revisions to laws and enforceable policies. Ongoing regional coordination among regulatory agencies and the scientific community is critical to both identify challenges and to develop a broad consensus for solutions that can lead to these refinements in policy and permitting.

composition affects target species. Because the risks are not yet identified, establishing a surveillance-monitoring program is recommended.

IMPACTS FROM INVASIVE *SPARTINA*

In recent decades, the San Francisco Bay tidal marsh has been invaded by an introduced cordgrass (*Spartina alterniflora*) from the eastern coast of the United States and subsequently by more invasive hybrids formed between the Pacific and Atlantic species. As an ecosystem engineer, invasive hybrid *Spartina* (referred to



Invasive *Spartina*

interchangeably below) can affect tidal wetland functions, such as succession, productivity, and habitat structure. On the lower end of its tidal elevation range, invasive *Spartina* has grown down into mudflat elevations, converting mudflat into hybrid meadows. On the higher end of its elevation range, invasive *Spartina* has displaced the dominant marsh plain species—perennial pickleweed, gum plant, and saltgrass—to become dominant in some marshes. In restoration sites, hybrid *Spartina* has formed dense monocultures absent of the channel complexity and diverse mid-marsh zonation typical of native-dominated marshes.

The effects from invasive *Spartina* can be beneficial in certain ways. The ability of tall, dense hybrid *Spartina* to trap sediment and cause rapid vertical accretion not typical of native marshes could help marshes endure in the face of sea-level rise. A co-benefit of using hybrid *Spartina* to hasten accretion is the provision of increased cover and foraging substrate for the endangered Ridgway's rail. The population of Ridgway's rails grew when invasive *Spartina* expanded and declined when the cordgrass was aggressively controlled. However, the association between Ridgway's rail and hybrid *Spartina* was not ubiquitous; rather, the rails appeared to take advantage of the invasive plant mainly in places where cover and high-tide refuge were lacking to begin with.

On the other hand, studies of the effect of hybrid *Spartina* on wildlife communities show the potential for significantly harmful effects. First, native cordgrass (*Spartina foliosa*), which also facilitates marsh accretion, could be at risk of extinction due to the loss of low marsh from sea-level rise and genetic assimilation by the invasive hybrids. Furthermore, conversion of mudflat to hybrid *Spartina* meadows would equate to the loss of foraging habitat for more than 500,000 shorebirds that rely on the mudflats of the bay for refueling during migration. The altered marsh plain plant structure of invaded marshes causes a loss of habitat for the endangered salt marsh harvest mouse. Invaded marshes have also altered benthic invertebrate communities in terms of biomass, diversity, and functional group identity. The shift is most marked in converted tidal mudflat, where the invertebrate community shifts from surface feeders that primarily consume microalgae to belowground feeders that primarily consume plant detritus. Finally, hybrid *Spartina* propagules could spread directly from the San Francisco Estuary to as far as Oregon, and indirectly over generations to British Columbia and Alaska.

Because of concerns about the negative effects of invasive *Spartina*, the California State Coastal Conservancy and the US Fish and Wildlife Service's Don Edwards San Francisco Bay National Wildlife Refuge prioritized the eradication of invasive *Spartina* from the San Francisco Estuary through the formation of the Invasive *Spartina* Project (ISP). Since 2005, persistent control efforts by a region-wide coalition of ISP partners have reduced the footprint of the hybrid from over 800 acres to 29 net acres as of the 2013 treatment. Complete genetic eradication of *Spartina* is notoriously difficult, as evidenced by similar situations elsewhere in the world. Monitoring for and removing invasive phenotypes (those plants that act

in the environment like an invasive hybrid) is a critical aspect of the later phases of the eradication plan, given that the removal of every *Spartina alterniflora* gene may be impossible. The possibility of using invasive *Spartina* to stimulate marsh accretion in the future is acknowledged as a tool that could be used if the loss of marshes becomes dire as sea levels rise. For now, innovative approaches to adding high-tide refuge (such as marsh mounds and floating islands) and aggressive revegetation of treated marshes are under way to provide important additional cover for Ridgway's rail and other wildlife in previously invaded marshes.

Summary of Consequences for Wildlife

Tidal marsh birds and mammals are particularly susceptible to climate change. Concerns include the loss of habitat due to sea-level rise; the inundation of habitat during winter extreme tides and storms and during the breeding season, coupled with a lack of refugia; and elevated predation due to human-associated predators (including crows, ravens, and cats) as well as to increased access to tidal marsh by predators. Impacts to the transition zone may further imperil marsh wildlife, as well as transition zone species. During major flood events, tidal marsh wildlife tends to be concentrated in the transition zone, which can therefore serve as an important foraging area for many species of predators. The transition zone supports the migration and dispersal of plant and animal species. It enables them to move along the bayshore between patches of preferred baylands habitat.

Migratory and far-ranging species using the baylands, such as shorebirds, waterfowl, and other waterbirds, will be affected by changes in the bay as well as by conditions elsewhere. Similarly, anadromous fish will be affected by changes in the bay as well as by upstream and downstream conditions. San Francisco Bay may become more important to these species if their ranges shrink due to inhospitable conditions at the extremes of the ranges, or if they arrive in poorer condition during migration. Managed ponds, which support large populations of waterfowl and shorebirds, will require intensive management to persist in the face of sea-level rise.

Changes in water quality, temperature, and bathymetry are expected to affect aquatic species, though in many cases the consequences of these changes are unclear.

Considerations for Actions Related to Wildlife

Habitat restoration and conservation on a landscape scale is critical to meeting the needs of wildlife in this ecosystem, which has experienced severe habitat loss and degradation over the past two centuries. Equally important is the management of the wildlife populations themselves in the face of increasing frequency and severity of extreme climatic conditions. Thus, management actions must address long-term trends in climate and habitat as well as sudden catastrophic events. Ensuring resilience means reducing the mortality of adults and juveniles, increasing reproductive success, promoting successful dispersal, and maintaining phenotypic and genetic diversity of both plants and animals.

Changing conditions and limited resources will likely lead to further conflicts and trade-offs in managing for different species and natural communities. There is a

strong need for scientists, managers, and regulators to work together on approaches to scale up from species management to wildlife conservation at the community and landscape level.

The following strategies are critical to conferring resilience upon baylands wildlife:

1. ENSURE SUFFICIENT HABITAT EXTENT INTO THE FUTURE.

All baylands habitat types are important for wildlife, including tidal marsh, tidal flats, managed ponds, managed marshes, beaches, and transition zones. Sufficient habitat extent is the first step, but not the last, in ensuring the persistence of baylands wildlife.

2. PROVIDE HETEROGENEOUS HABITATS WITH ALL NECESSARY HABITAT FEATURES, LOCALLY AND ACROSS THE LANDSCAPE.

A healthy baylands ecosystem is characterized by heterogeneity at multiple scales. A mosaic of habitat patches allows an array of species to persist, but only if the components of the mosaic are functionally connected. Plants and animals must be able to move from one patch to another, at short (daily) or long (annual, decadal) time scales. Thus, heterogeneity is a desired condition that results from dynamic ecological processes operating within a changing landscape. The management goal is dynamic heterogeneity rather than static heterogeneity; the desired landscape is heterogeneous and changes with time.

Habitat heterogeneity encourages the survival of local populations of plants and animals by promoting genotypic and phenotypic diversity. This diversity allows for adaptive evolution in response to changes in habitat conditions. Adaptation is known to occur at the margins of habitats, including ecotones, where individuals encounter the limits of their physiological tolerance to environmental factors. Maintaining heterogeneous and connected habitats can help baylands wildlife respond adaptively to changing conditions on different time scales.

One important habitat feature that contributes to heterogeneity is the width, extent, and vegetation structure of the marsh–terrestrial transition zone (see Connections to the Watersheds: The Estuarine–Terrestrial Transition Zone above). It is equally important to focus on the nature of the terrestrial habitat that borders the baylands, because predators and invasive species often enter the transition zone from the terrestrial side. Upland areas that will accommodate wide transition zones and marsh migration space are likely to become rare, so all opportunities should be considered.

Refuge habitat from predation and extreme water levels is already of high importance and will become more so. Refugia may also be needed from drought, which leads to the drying of ponds and hypersalinity.

Design considerations can allow smaller areas to do more for their dependent wildlife populations. For example, topographic relief and a highly dendritic, sinuous network of tidal channels are of great value to marsh wildlife. Enhancing topographic complexity through the creation of marsh mounds and berms can enhance marsh heterogeneity, increase plant species diversity, and provide barriers to water flow and refuge from high-water events. Similarly, designing restored marshes so they have complex channel systems will increase their habitat value.

Similarly, management considerations can improve habitat quality and support denser wildlife populations. For example, salinities have generally been lowered in managed ponds in both the North and South Bay, as part of a long-term management strategy to manage some ponds for wildlife and ultimately convert other former salt ponds into tidal marsh. The result has been a substantial increase in diving and dabbling ducks, but such change has not necessarily been as favorable for shorebirds, some of which rely on the high densities of invertebrates found in hypersaline ponds. To counterbalance such a change, reducing the water depth in managed ponds can increase the accessibility of foraging habitat for shorebirds. Recent reductions in water depth in some managed ponds have led to increases in shorebird numbers. Thus, pond management can be optimized to maintain a desired balance of salinity and water depth to support diverse waterbird species. In this way, a reduction in acreage of managed ponds can still result in a greater abundance of shorebirds and diving ducks, provided the habitats can be carefully designed and closely managed according to key parameters.

3. ADDRESS OTHER STRESSORS.

A resilient population is better able to tolerate the effects of change, especially extreme events such as droughts and floods. A reduction of known stressors will help a population withstand new stressors, even if the effects of the new stressors cannot be precisely predicted. A resilient population has sufficient reproductive success and survival to offset mortality, including occasional catastrophic mortality, with some amount of buffer.

Hence, knowing reproductive and survival rates is important to assessing whether a species is in trouble. Where abundance has declined over time, research and management teams need to respond quickly to reverse that trend. Tidal marsh song sparrows have exhibited recent declines throughout the San Francisco Estuary due to low nest survival. Ridgway's rails have increased in number relative to the 1990s, but have decreased from 2007 to 2013, with low first-year and adult survival the prime contributors. Such studies indicate which life-history stage that management should focus on to augment resilience.

The following stressors should be reduced, independent of climate change, to increase population health and resilience.

- ◆ *Predation.* Predation affects adults, juveniles, and reproductive success (through the loss of eggs, seeds, etc.). See earlier discussion.
- ◆ *Contaminants.* These include methylmercury exposure for birds and mammals, pyrethroids for aquatic species, and emerging contaminants.
- ◆ *Invasive and nuisance species.* Management that targets invasive and nuisance species is often less controversial than other actions.
- ◆ *Human disturbance.* Disturbance by humans (often due to incompatible recreational use) can be reduced. Shorebirds and waterfowl benefit from reduced disturbance, as do harbor seals.
- ◆ *Disease susceptibility.* Susceptibility can be reduced through the improvement of a species' physical condition, which in some cases reflects prey availability.

4. INCREASE RECRUITMENT AND DISPERSAL SUCCESS THROUGH HABITAT CONNECTIVITY.

For wildlife populations to be robust and resilient, successful dispersal is critical. Small, isolated populations are vulnerable to extinction, while meta-populations connected by dispersal are much more likely to persist. Baylands habitats are already fragmented, and future change is likely to exacerbate the problem. For these reasons, habitat connectivity will become even more important in the future.

Furthermore, current baylands habitat configurations are expected to change substantially. Habitat patches that are currently suitable will no longer be suitable, but other areas will become more suitable. As a result, wildlife populations will need to be able to move in order to persist, and that will require connectivity of existing and future suitable habitat.

Unfortunately, dispersal ability is limited for many baylands species of concern. This is especially so for a suite of endangered or rare marsh plant species. In addition, vernal pool plants and invertebrates, longjaw mudsucker, tidewater goby, salt marsh harvest mouse, and the baylands shrews appear to have limited dispersal abilities. Black rails and Ridgway's rails demonstrate low dispersal rates, even when such movement would be adaptive.

Restoration designs can address habitat fragmentation by targeting functional connections that allow movement and dispersal between patches. Habitat corridors should be planned and restored, taking into account likely changes in habitat configurations. Habitats do not necessarily need to be contiguous, but target wildlife species do need to be able to move between patches successfully. Highways, levees, and other structures can be designed or retrofitted to allow successful wildlife dispersal.

For some species of limited dispersal ability, or for which current barriers are too high, the active translocation of individuals will be required as currently occupied habitats are lost or degraded and new habitat is produced in other areas.

5. MANAGE FOR DYNAMIC LANDSCAPES.

The changing and unpredictable nature of future habitat configurations will require greater planning and monitoring in order to ensure successful wildlife outcomes. Restoration designs should improve on the present landscape by providing more high-quality, connected, sustainable habitat patches. In addition, restoration projects should anticipate where mudflats or tidal marsh may migrate in the future, and design accordingly. Management actions should fit into a regional vision of a landscape of diverse, heterogeneous, connected, sustainable habitat patches both now and into the future.

Changing landscapes will also require wildlife populations that can adapt to new conditions. Many species of concern in the baylands are composed of genetically distinct populations or subspecies, including tidal marsh song sparrows, California red-legged frogs, salt marsh harvest mice, baylands shrews, black rails, and salmon. This valuable genetic diversity reflects an adaptation to local conditions. These genetically differentiated populations need management to maintain their resilience and facilitate the recolonization of suitable habitat following catastrophes. Recolonization may occur by a different subspecies or population than was originally present. This may be a natural aspect of rapid evolution brought on by the impacts of climate change. Maintaining spatially distributed and connected habitat

Complex landscapes help drive population diversity and resilience.



for these species is important for preserving genetic diversity as the foundation of future adaptation.

Isolated populations, such as those of some rare marsh plants and vernal pool invertebrates, represent unique products of adaptation and genetic drift. These isolated populations have very little crossbreeding. Thus, the loss of a population due to catastrophe may represent a complete loss of some genetic diversity and must be avoided.

6. MANAGE FOR UNCERTAINTY.

One approach to addressing the uncertainty regarding the timing of changes is to develop triggers for management action: when thresholds are crossed, management action is triggered. Thresholds of concern for wildlife include

- ◆ the recurrent overtopping or breaching of levees
- ◆ a clear need for new hydraulics or significant reconstruction or armoring
- ◆ low-marsh vegetation dominating the marsh plain
- ◆ large-scale conversions of brackish marsh to saline marsh

Another approach is to address knowledge gaps, of which there are many. Baylands managers suffer from a widespread lack of basic information for many species of concern. This is the case not only for rare species, such as the baylands shrews, but also for common species, such as river otters. River otters are becoming much more common in the baylands, but whether that is the sign of a burgeoning population or of movement downstream from more disturbed areas upstream is unknown. For many species, scientists don't know if populations are currently stable, declining, or increasing. For wintering species and migrants, even if information is available about current trends for the San Francisco Estuary, it may be missing for

other areas, such as breeding grounds. Population models that incorporate environmental variability can begin to fill these knowledge gaps. Such models can be used to evaluate resilience, explore how resilience can be increased, and identify thresholds of concern.

CARBON SEQUESTRATION AND GREENHOUSE GASES IN THE BAYLANDS

Many of the most fundamental actions recommended in this report offer a co-benefit of sequestering carbon or reducing the emissions of greenhouse gases that contribute to global warming and climate change. Managing carbon and these gases more explicitly as a part of baylands conservation may allow restoration and management practices to mitigate climate change at the same time as adapting to it. The following discussion summarizes our current understanding of carbon dynamics in the tidal marshes of the Bay, building on detailed information found in Science Foundation chapter 6.

Wetlands are important in the global carbon cycle. They serve as major carbon sinks, due to their fast rates of primary productivity, large standing biomass, and their tendency to retain carbon as peat. While most urbanized estuaries are net consumers of organic matter and, therefore, sources of carbon dioxide (CO₂) to the atmosphere, net metabolism in the San Francisco Estuary overall appears to be nearly balanced.

Thoughtful management of San Francisco Estuary's baylands can play a part in global climate regulation. As conditions evolve, baylands management is increasingly being understood to play a role in carbon storage and fluxes of greenhouse gases. California has established a state cap-and-trade system in order to reduce emissions. Though further behind than forestry projects, the management of organic soils on drained coastal wetlands and the restoration of these wetlands are being eyed as potential future offset projects. Knowledge gained here, where planning activities have greater support and the capacity to be more forward-looking, can be transferred to other parts of the country and the world.

At the current price of a carbon credit under the California market (approximately \$12 per ton of CO₂), carbon financing would not underwrite the cost of a wetlands restoration project. However, those funds might enable existing staff to maintain a science program to provide the monitoring, reporting, and verification of carbon credits. It has yet to be seen what the price of carbon will be in coming years, but given the need for greenhouse gas reductions, the price is likely to rise.

Carbon Sequestration

Carbon cycling through plant growth, decomposition, sequestration, and greenhouse gas emissions directly affects the sustainability of tidal wetlands. Tidal wetlands remove CO₂ from the atmosphere as they accumulate organic matter, which helps them grow vertically in the tidal frame. In this sense, carbon sequestration in tidal wetlands integrates across both adaptation and mitigation for climate change. Within the baylands, carbon sequestration is of particular management interest, because

of the possibility of reversing the loss of elevation due to subsidence (see section Drowning and Accretion above). Peat accumulation is most rapid in freshwater marshes and declines as salinity increases, creating more organic matter in the soils from the less saline parts of the estuary (fig. 23). If tidal marshes in the bay can grow vertically and migrate laterally with sea-level rise, then they will sequester more carbon. However, if marshes drown and become unvegetated mudflats, they largely lose the ability to produce and store carbon.

Significant stocks of carbon have accumulated gradually within baylands soils over time. Carbon sequestration in existing tidal wetlands averaged about 80 g C/m²/yr (grams of carbon per square meter per year) over the last century. Although sequestration data are available for mature wetlands within the estuary, no data exist for recently restored wetlands. Given the high rates of sediment accretion in recently restored areas, sequestration rates in these wetlands could be higher than in natural tidal wetlands over the short term. Based on projected restoration plans across the bay, a total of 0.28 to 0.30 million metric tons of carbon could be sequestered in restored tidal wetlands across the San Francisco Estuary.

Research on wetland greenhouse gas biogeochemistry in the San Francisco Estuary has been advanced primarily in the delta, where the majority of former wetland acreage now exists as drained subsided organic soils. Drained organic-rich soils continue to release CO₂ over long periods, and prolonged emissions are evident in drained areas of the delta. Conversely, emissions from more mineral-rich soils typically decline or halt over time, and wetland restoration can reinitiate the slow process of carbon sequestration once vegetation is reestablished.



Management of carbon in the baylands can be integrated with habitat objectives.

Approaches to grow wetlands in order to accumulate peat and reverse subsidence have been tested in the delta for over 10 years, but not in the bay. Opportunities to apply these approaches should be examined for the baylands, even though peat accumulation is somewhat slower in brackish and salt marshes. One of our greatest challenges is filling the subsided areas of drained baylands behind levees. Subsidence-reversal techniques may fill some of that volume. In locations where natural water supplies would be too saline for reed growth, freshwater could be derived from redirected wastewater outflow.

Greenhouse Gas Emissions

In addition to emissions of CO₂, some wetland soils can release nitrous oxide (N₂O), a greenhouse gas 310 times as potent as CO₂, and methane (CH₄), a greenhouse gas 34 times as potent as CO₂. Given these substantial greenhouse effects, both N₂O and CH₄ must be incorporated into any evaluations of overall carbon dynamics and greenhouse gas emissions. Nitrous oxide emissions are greatest in wetlands affected by high fertilizer loads. Methane emissions occur in wetlands with standing water, as well as in drainage ditches and duck ponds, and are more likely to occur at salinities below 18 parts per thousand (ppt), or about half the salinity of seawater.

In addition to carbon dioxide emissions, methane is probably being released from drainage ditches and areas of standing, low-salinity, and brackish waters on drained baylands. Nitrous oxide is likely being emitted from diked baylands with cattle or where nitrogen fertilizer is used. Suisun Marsh is very likely an important source of ongoing CO₂ emissions. The diked areas of Suisun Marsh are also likely producing methane from beneath standing water in ditches and duck ponds. Reducing ongoing emissions may have greater greenhouse gas benefits than the rebuilding of peat through restoration projects.

Considerations for Actions Related to Carbon Management

The restoration of duck clubs to tidal marsh would provide multiple benefits by sequestering carbon, reversing subsidence, and simultaneously reducing net greenhouse gas emissions. Current duck club management involves standing water over organic soils, which may reduce CO₂ emissions and protect soil carbon stocks in comparison to diked areas. However, this management could also increase CH₄ emissions. Further quantification of emission benefits under different land uses is needed.

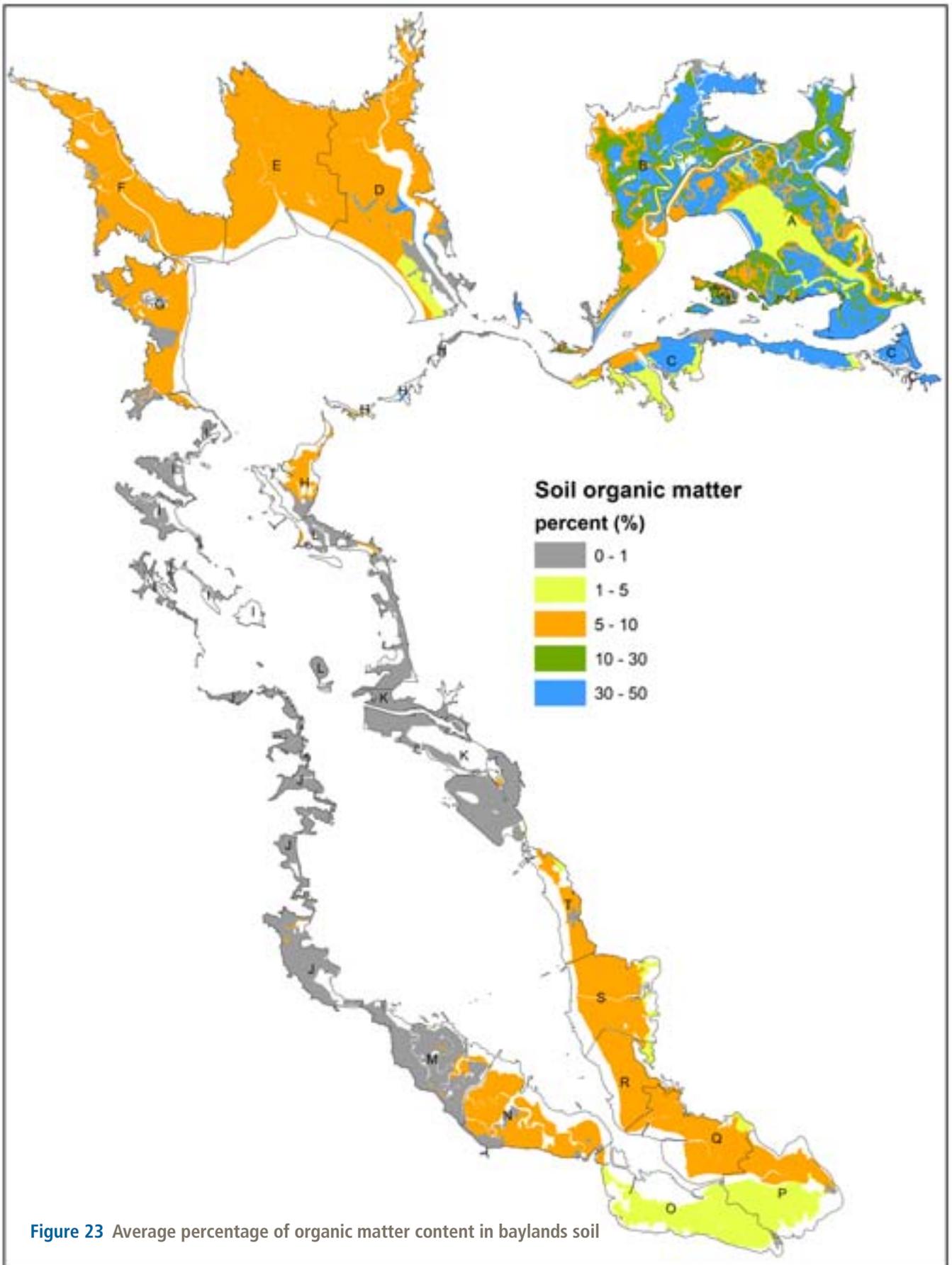


Figure 23 Average percentage of organic matter content in baylands soil

Box 8 Challenges to Funding Restoration and Long-Term Monitoring, Maintenance, and Management

Despite the recent support for, and the success of, restoration efforts, long-term funding for baylands management is uncertain. Securing funding for scientific initiatives and monitoring to guide restoration management has been an ongoing challenge.

Several traditional public funding sources for wetland acquisition and restoration are on the decline. State bonds, one of the key sources of funding over the past decade, have become less reliable, and their short-term cycles and capital focus have left gaps in the ability to assess the success of innovative approaches through consistent monitoring. San Francisco Bay, unlike other major estuaries, receives no federal programmatic funding; thus federal funds must be congressionally appropriated through the annual budget process, allocated by agencies, or won through nationally competitive grant programs. Private sources to fund restoration of the baylands remain limited.

As a result, project funding is often restricted to construction, planning, and permitting. Funder guidelines may not allow for all aspects of project planning, design, monitoring, and data sharing; so in general, project managers do not build long-term monitoring funding into a construction budget. For example, large Corps of Engineers restoration projects

provide federal funding for monitoring and adaptive management for a limited period of time geared toward establishing a project's "success"; subsequent monitoring is assigned to the nonfederal sponsor.

This situation fragments evaluation processes that increasingly demand continuity for success. Restoration depends on consistent and interpretable monitoring data, yet data sets vary, as do protocols and monitoring term lengths. The lack of baseline inventories or long-term data sets complicates the ability of managers to use information for management purposes. Most monitoring is done to meet permit requirements that can be punitive if not met, and they can vary from project to project or permitter to permitter. Therefore, regulatory monitoring data that are used to satisfy permit requirements are often less useful than they could be to guide management and future restoration.

Monitoring and evaluating a project should guide adaptive management in practice, not just in theory. Dedicated funding is necessary to integrate existing programs, fill data gaps, and manage data in a way that managers can use. Monitoring programs, both regulatory and nonregulatory, should be designed to address efficacy. Are conservation efforts having the desired effects? If not, why not? What types of management actions would be necessary to bring about desired changes?

Effective monitoring will remain necessarily diverse but can be aligned. Ambient monitoring is longer term and important for answering questions about climate change. Static monitoring is needed to provide a full assessment for management purposes, and outcome monitoring on targets also needs to be conducted.

The San Francisco Bay Joint Venture Monitoring and Evaluation Plan Phase I (2011) identifies high-priority research and recommends the development of consistent protocols that answer clear



Biologists survey shorebirds.

management questions. It suggests resolving the lack of consistency in data management, analysis, and access. Addressing collaborative data-management needs will require not only new financial resources but also changes to internal agency and organizational policies.

Near-Term Challenges and Options for Project Implementation and Monitoring

Government and private funding sources need to be further diversified. Efforts should continue to develop a federally authorized program, such as the San Francisco Bay Restoration Act's proposal for a geographic program within the Environmental Protection Agency. Dedicated funding for wetlands should continue for state programs such as the San Francisco Bay Area Conservancy and the Wildlife Conservation Board. The state-legislated San Francisco Bay Restoration Authority is authorized to secure local and regional funding for wetlands restoration, but it has not yet secured such funding; regional ballot measures should be developed at a level adequate to successfully leverage nonlocal funds. Legislation, ballot language, and guidelines for new funding sources should allow funding for longer-term monitoring and management as well as wetland construction.

Nontraditional partnerships are being formed to leverage resources to both fund and deliver restoration projects. Examples include the integration of restoration into flood control and other Integrated Regional Water Management (IRWM) projects. The restoration community is coordinating with the dredging community to resolve issues that can lead to a greater reuse of dredge material to build marshes more quickly, enabling them to keep pace with sea-level rise. Cost has been identified as a major roadblock to expanded reuse; so it is necessary to find financial options that make reuse more viable as well as address persisting regulatory hurdles. In particular, Army Corps dredging projects should be authorized as restoration projects as well as maintenance projects to make reuse from their projects

feasible. Such integrated alliances toward delivering habitat values will only become more important as climate change quickens.

Managers should continue to take advantage of fines and mitigation funding for public works projects. Regulatory agencies have directed fine and mitigation money toward high-priority restoration sites in the region, linking funding as closely as possible to the infraction or impact. This cooperative approach should continue to include other projects that address the impacts of sea-level rise.

Monitoring criteria should be built into project designs to integrate planning and project delivery with management and should be reflected in funding prioritization criteria. Regulatory requirements represent opportunities to expand the existing sphere of knowledge related to wetland restoration in the bay and should be framed to (1) support the ease of permitting mechanisms for restoration projects and (2) inform improved restoration design and management practices. Existing information, including restoration projects' monitoring data, should be collected and consolidated, leading to a more expedited permit process.

Challenges should be met through new partnerships.

