Science Foundation Chapter 3
Connections to the Bay

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INTRODUCTION

The open waters of the Bay (defined here to include San Francisco, San Pablo, and Suisun Bays) 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. This Connection brings the effects of remote changes in the watershed and the ocean to the Baylands.

This chapter describes the effects of climate and other long-term changes that specifically affect the Bay Connection either through effects of the Bay on the Baylands, or the reverse. Changes within the open water are addressed here only if they are likely to interact with the Baylands. This chapter includes a discussion of the Bay Connection for nutrients, organic matter, and biota; some aspects of sediment movement are touched on here but that topic is addressed more fully in Science Foundation chapter 2 This chapter also provides a partial update to the Subtidal Habitat Goals Report (2010), which laid out recommendations for research, protection and restoration of valued subtidal resources.

Our approach is qualitative, in that the details of many of the interactions are uncertain but will likely involve multiple drivers and a network of responses (Roos 1989). For example, rising sea level will interact with sediment availability, salinity, construction of seawalls and levees, and local wind patterns, which together will affect water clarity, local circulation, and habitat suitability for submerged aquatic vegetation (SAV), intertidal wetland vegetation, and animals. These combined interactions will affect sediment availability for marsh replenishment and maintenance and shoreline protection.

The approach in this chapter is based on the concept of risk, which is the product of probability and consequences. The five scenarios (see New Understanding: the Baylands and Climate Change, Appendix D) bracket ranges of likely future conditions within the estuary for temperature, sea level, freshwater flow, and sediment supply, and include one storm scenario. These trends will likely have substantial consequences for the estuary and therefore impose substantial risks. Other trends may have consequences for the Bay but are less well predicted, or are predicted by some analyses and not by others (Science Foundation chapter 1. Still others are likely to occur as a result of direct human interventions. Some events with a low annual probability may lead to severe consequences, notably an earthquake resulting in the collapse of levees in the

Delta and Suisun Marsh, which would alter the tidal prism and the salinity distribution throughout the estuary.

The probability of a particular outcome is the product of probabilities of each link in the causal chain from the driver of change (e.g., rising sea level) to the final outcome (e.g., loss of eelgrass). In this chapter we focus on the changes and events having high probability or large consequences.
We seek to answer the following questions:

- What are the key concerns among the effects of long-term changes in the Bay on Baylands habitats, or the effects of Baylands on open waters?
- What scientific research or monitoring would be most useful in reducing uncertainty in projections of impacts to the Bay Connection?
- If important negative impacts are expected, are there management actions that could increase the resiliency of the Baylands or open waters?

Case studies (Science Foundation chapter 3, appendix 3.1) have been developed to make the general discussion here and in Science Foundation chapter 5 more specific, particularly with regard to how individual species or groups of species may respond and what might be done about them.

THE BAY CONNECTION TODAY

The Bay and Baylands are linked dynamically through the movement of water, sediments (Chapter 2, nutrients, organic matter, and organisms. Tidal fluctuations in water level in the ocean produce currents that move water between the ocean and the Bay, and between Bay and Baylands. Freshwater inflow from the major rivers and smaller tributaries alters water level and sets up estuarine salinity gradients. Water flows within the Bay are further modified by atmospheric pressure and wind along the outer coast and, locally within the Bay, wind-driven waves and wind set-up of water level. These links provide mechanisms by which changes in the atmosphere, ocean, and watershed can influence the Bay and thereby the Baylands.

Movement of water also moves sediments, which segregate by size into larger grain sizes in areas of energetic waves and currents, and smaller grain sizes in calmer areas. Nutrients and organic matter are transported by currents, and organisms are transported by currents and their own swimming. Tidal movement of water between the Bay and adjacent marshes oscillate: the water moves in on the flood, mixes within the marsh, and moves and out on the ebb. Dissolved substances, particles, and organisms are carried with the water, providing a mechanism both to nourish the marsh (sediment, nutrients, organic matter, organisms) and to remove materials from the marsh (sediment, organic matter, organisms). By moving from place to place, organisms also transport organic matter, e.g., when they spawn in one area and rear in another.

Exchange of Organic Matter and Biota

Marshes and other shallow areas produce large quantities of organic matter per unit area because of their extensive vegetated surface exposed to sunlight and the continual supply of nutrients from the Bay and from land. Primary productivity within a marsh includes that by the rooted plants, attached algae, epiphytes, and benthic and planktonic microalgae. Because of high light levels, growth of plants generally exceeds respiration by all organisms within a marsh, resulting in net production of organic matter. Over time this excess production must be either buried or exported to the adjacent Bay and terrestrial areas. This export may occur through tidal exchange between the marsh and the Bay, or through active or passive movement of organisms that feed in the marsh but die outside the marsh.

Export of organic matter from marshes to adjacent estuarine waters was first considered as the "outwelling hypothesis" (Odum 1980, Nixon 1980), by which organic matter that is readily digested by organisms provides an important subsidy to nourish adjacent waters of the estuary. The outwelling hypothesis originated in studies of extensive, rich marshes on the Atlantic coast of the United States. Even there, quantitative demonstrations of the importance of outwelling to estuarine or coastal foodwebs were few (Dame et al. 1986). The difficulty arises from the technical challenge of making enough measurements to quantify a small net flux in a large tidal signal with high variability (Dame et al. 1986) and the numerous modes by which that flux can occur (McKee et al. 2006). In addition, dissolved and particulate organic matter produced by rooted vegetation can consist of material that is resistant to biological breakdown and therefore largely unavailable to estuarine pelagic foodwebs compared to that produced by phytoplankton (Sobczak et al. 2002, 2005). Foodwebs within the diverse marshes of the San Francisco Estuary are supported more by local production of rooted plants and epiphytes than by estuarine phytoplankton (Howe and Simenstad 2011), while pelagic foodwebs rely more on phytoplankton production (Grimaldo et al. 2009).

Benthic and planktonic microalgae (phytoplankton) produced in a marsh are directly available to zooplankton and other consumers. Production by these microalgae can be high in marshes and other shallow areas where light can penetrate to the bottom. Therefore a marsh could export living phytoplankton or their zooplankton consumers to adjacent estuarine waters. However, the flow of plankton to and from a marsh depends on both production and consumption within the marsh, including consumption in shallow waters of phytoplankton by benthic grazers (illustrated for flooded islands by Lopez et al. 2006), or of zooplankton by small fish that seek food and shelter in shallow areas (Kimmerer and McKinnon 1989). Marshes can be simultaneously sinks for some zooplankton (copepods) and areas of aggregation for others such as bottom-oriented larvae (Mazumder et al. 2009). Thus, marshes may act either as net sources or sinks for plankton in the adjacent waters, depending on the availability of habitat for small fish and the degree of colonization by benthic grazers such as clams.

The exact details of the exchange processes depend on the physical configuration of the marsh including residence time of the water and the biological composition, i.e., the kinds and abundance of producers and consumers within the marsh, especially the transient organisms. Few of these aspects have been examined in marshes of the San Francisco Estuary. Long-term studies of the channels of Suisun Marsh have revealed a lot about fish assemblages (e.g., Matern et al. 2002, Feyrer et al. 2003) and jellyfish and some zooplankton (Wintzer et al. 2011, Meek et al. 2013), and some detailed studies of exchange processes have been undertaken (Culberson et al. 2004). A general conclusion from this work is that the channels of Suisun Marsh are largely isolated from the rest of the estuary, presumably because of long residence time, such that the assemblages of species are somewhat distinct and vary separately from those of the nearby open waters. The South Bay Salt Ponds, which began to be reconnected to the tidal action of the Bay in 2006, are highly productive and may export organic matter to nearby estuarine waters, although the form of that export has not been determined (Thebault et al. 2008).

Use of Marshes by Fish and Crustaceans

A marsh could subsidize or be subsidized by an estuarine foodweb through the movements of fish and crustaceans (both also referred to as nekton, active swimmers that are able to move independently of water currents) into and out of the marsh. Nekton feeding in the marsh but spending substantial time outside the marsh will transport organic matter from the marsh to the open water (Kneib 1997). This can occur in two ways: first, organic matter may be transported through repeated bouts of feeding in the marsh by organisms that otherwise reside in the open waters. Second, nekton may use the marsh as a nursery, rearing to a certain size before leaving the marsh to complete their life cycle in the open water. In both cases there is a two-way influence: biomass flows to the Bay where it may support bay foodwebs, and the transient or rearing fish prey upon marsh organisms, potentially exerting an important control on the size and species of biota resident in the marsh, and thereby on other ecological processes.

The reverse pattern whereby nekton mediate a flux of organic matter into a marsh is probably less common because of the high organic production within marshes. Nevertheless, mysid shrimp moved into a marsh at China Camp where they were apparently consumed, implying a flux into the marsh (Dean et al. 2005).

The species of nekton typically found in marsh channels include marsh resident species and species that are characteristic of open waters (see the case studies for herring and anchovy, appendix 3.1). Resident species, as used here, means those species that are more abundant in marshes than in the open waters; transient species are those that either use the marshes seasonally (Matern et al. 2002) or sporadically, including those that use marshes as nurseries (below). The particular species found in any marsh depends somewhat on the salinity of the water there, although some species such as the non-native Mississippi silversides and striped bass occupy marshes over a range of salinity (Moyle et al. 2013). Resident species include sedentary fish such as sticklebacks, sculpins, and gobies, which feed principally on amphipods and other resident crustaceans in the marsh channels and marsh plain (Visintainer et al. 2006). Transient species include the more abundant species of the open waters, such as northern anchovy, Pacific herring, starry flounder, and striped bass, and migrating species such as salmon.

The South Bay Salt Pond Project has documented large numbers of juvenile fish inside restored salt ponds just a few years after breaching, as well as very high productivity of invertebrates such as shrimp as soon as one year after breaching (Hobbs et al. 2012). This high productivity is apparently exported through consumption by larger predators of the open waters (Hobbs et al. 2012). Pilot subtidal restoration projects have documented reproduction of native oysters, bay shrimp, bay gobies, Dungeness crab, red rock crabs, and nudibranchs (State Coastal Conservancy 2013). This may contribute to food resources for other species that use adjacent marshes, but the extent of this support has not been investigated.

Nursery Function

Some species of nekton may use marshes as nursery habitat, growing in marshes to a certain size and then migrating out to open water (note that this does not include species that reside in marshes throughout their lives). On the east coast, numerous coastal and estuarine fishes and other nekton, including some that support major fisheries, must spend some part of their juvenile life stages in marshes. These include species such as herring and anchovy (Ayvazian et al. 1992). However, no fish species of the San Francisco Estuary appears to require marshes as nursery habitat. For example, northern anchovy are by far the most common fish in the Bay (see the anchovy case study, appendix 3.1) yet are uncommon in marshes of the

San Francisco Estuary (Visintainer et al. 2006, Gewant and Bollens 2012). Pacific herring use shallow subtidal areas including marsh channels for spawning, laying sticky eggs on surfaces such as rock and vegetation (see the herring case study, appendix 3.1), but young herring rear mainly in the open waters of the estuary. Species such as striped bass and longfin smelt can be abundant in Suisun Marsh but are also common in the nearby open waters at all sizes.

There are several potential reasons for the lack of a life history requiring rearing in marshes. First, the species with this life history may have been lost, or they may have adapted by shifting their rearing to other habitats, as marshes were eliminated from the estuary. Moreover, the relative lack of large estuaries along the Pacific coast compared to the Gulf and Atlantic coasts may have limited the evolution of obligate use of estuaries and marshes as nurseries by west coast species.

Nursery support of the entire estuary may be poor for juvenile Chinook salmon, which grow slowly and move rather quickly through the San Francisco Estuary (MacFarlane 2010). This contrasts with the extensive, long-term use of marshes and shallow waters as nurseries by juvenile salmon in Pacific Northwest estuaries (Miller and Simenstad 1997, Bottom et al. 2005).

There is little published information on the extent to which restoration of marshes will restore nursery function to the marshes, and the species likely to use that function. Intertidal habitat is important to young Dungeness crab in Willapa Bay, WA (Holsman et al. 2003, 2006). Additional intertidal habitat in the saline reaches of San Francisco Bay may provide more habitat for crabs and some other species, but the importance of this habitat for these populations here is unknown.

Links within the Open Waters of the Estuary

Although the San Francisco Estuary can be considered a single water body (Kimmerer 2004), its size and geomorphic complexity result in considerable heterogeneity. For example, different seasonal and long-term patterns of phytoplankton biomass occur in the Delta, Suisun Bay, and South Bay (Kimmerer 2004, Cloern and Jassby 2010). Thus, most studies of estuarine processes consider only parts of the estuary. The geographic scopes of individual management programs and plans are also usually restricted to particular regions of the estuary; for example, the scope of this document excludes the Delta. Nevertheless, tidal currents, the net flow set up by river flows, the influence of salinity stratification, and the movements of organisms all link the segments of the estuary together.

Links between the Delta and the rest of the estuary are more unidirectional than links between say, San Pablo and Central Bays, because tidal currents are weaker so the net river-derived currents are more important. Still the river-derived current is small (a few percent of tidal currents in dry summers), so tides remain an important mechanism for transporting substances and organisms (e.g., Figure 29 in Kimmerer 2004). Under present conditions, the Delta supplies freshwater that opposes intrusion of ocean salt, nutrients largely from wastewater treatment plants (Dugdale et al. 2007), phytoplankton that subsidizes the low-productivity brackish region of the northern estuary (Kimmerer and Thompson 2014), and zooplankton from freshwater into the brackish region (Kimmerer unpubl.).

The Gulf of the Farallones (GOF) is likewise connected to and not particularly distinct from the marine-influenced Central Bay in terms of biota and physical processes. Exchange between Central Bay and the GOF exports 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.

FUTURE CHANGE: MECHANISMS AND CONSEQUENCES

How will long-term change affect Baylands through the Bay Connection? We present here an assessment of likely changes in the Bay Connection, notably those that arise through the movement of water, sediment, substances, and organisms between the Bay and the Baylands. This section focuses on the mechanisms and consequences of change within the Bay's ecology as a result of the drivers enumerated through the future scenarios (New Understanding: the Baylands and Climate Change, Appendix D), irrespective of the likelihood of changes in the drivers. The discussion starts with the physical environment, then examines direct influences on biota, and finally addresses biological interactions between Bay and Baylands and within the Bay. Case studies (appendix 3.1) furnish specific examples of the vulnerabilities and potential responses of several species groups and species, selected for their importance or likely responses.

Effects on Bathymetry and Sediment Supply

The bathymetry of the estuary exerts a strong control on circulation of water and sediments, and bathymetry is altered by erosion and deposition of sediments. Bathymetry in turn sets up habitat characteristics throughout the Bay and Baylands, and sediment supply can constrain the formation of Baylands newly connected to the Bay. Wind, biological activity, and human activities around the estuary also influence bathymetry locally.

Rising sea level will have numerous effects on Baylands, some of them direct (see Science Foundation chapters 1 and 2, and some indirect through the Bay Connection. The bathymetry of shallow areas of the Bay is in rough equilibrium between sediment supply and erosion due to wind waves and tidal currents. Therefore, the depth profiles of the future estuary will likely be similar to those today in areas where there is sufficient sediment supply and deeper in other areas because of higher sea level. The process of morphologic adaptation may lag sea level rise, producing temporary increases in water depth. One consequence of deeper channels is a greater tendency for stratification to develop, increasing salinity penetration into the estuary (Monismith et al. 2002).

Sediment availability depends on sediment supply as well as wind waves, currents, and local factors such as dredging and sediment stockpiles for nourishing wetlands (Science Foundation chapters 1 and 2. Several long-term trends (decreasing sediment supply, rising sea-level, increasing wind waves, and possibly an increase in vessel wakes and construction of seawalls) will combine to reduce the total sediment available within the estuary, although redistribution through these mechanisms may increase it locally. Sediment availability throughout the estuary will also depend on the extent of sediment trapping in restoration sites and in subsided islands in the Delta and Suisun Marsh that are reconnected to the estuary by catastrophic flooding, which may be more probable with higher sea level (Mount and Twiss 2005). The planned replumbing of the Delta includes two large tunnels designed to divert water from the Sacramento River during high flows, and with it about 8-9% of the annual sediment load down the river, in addition to extensive restoration of shallow habitat, both of which will reduce sediment loading from the Delta to the rest of the estuary (BDCP 2013).

Any increase in *wind speed* over shallow parts of the Bay will increase resuspension, which may increase or decrease sediment supply to marshes depending on local circulation patterns and water depth. An increased frequency of major storms would have a similar effect.

Water clarity depends on suspended sediment concentrations near the surface, which in turn is limited by the availability of erodible sediment (Schoellhamer 2011). Water clarity at any location is a complex function of sediment availability, local bathymetry, salinity distributions, current speed and direction, and wind waves. The waters of the Delta and Suisun Bay have become clearer over the last several decades (Kimmerer 2004), and suspended sediment concentrations have decreased in the last two decades (Schoellhamer 2011). These trends are likely to continue.

Contaminants can be released when sediments are resuspended through erosion or dredging. This is especially true for sediments deposited during the Gold Rush, which contain contaminants such as mercury and PCBs (McKee et al. 2006). Contamination in estuarine fishes such as striped bass has been attributed to concentration of contaminants such as mercury in the foodweb, and has led to recommended restrictions on human consumption of these species (Davis et al. 2012).

SAV beds (see the case study, appendix 3.1) interact with sediment supply. Their maximum depth is limited by light penetration and therefore turbidity, but they also trap and stabilize sediments. As with marshes, SAV beds can presumably migrate up-slope as sea level rises, but that depends on local bathymetry and wave energy. The seaward limit of SAV beds is generally set by light availability, although this limit may become deeper by a decrease in turbidity, favoring more extensive SAV beds.

Other Effects Propagating from the Ocean

Upwelling brings cool, nutrient-rich, low-oxygen, and 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. A recent meta-analysis of decadal-scale studies showed increasing intensity of upwelling-favorable winds along the California coast (Sydeman et al. 2014). This could increase the nutrient supply for plants and algae in the estuary. It can also bring in large numbers of diatoms and other plankton that thrive in upwelled waters (Cloern and Dufford 2005), as well as low-oxygen and low-pH (see below) waters. Low-oxygen events associated with pulses of upwelled water have been observed in South San Francisco Bay since 2006 (J. Cloern, pers. comm. to W. Kimmerer, 22 February 2015). A large region of low oxygen centered off Oregon has been expanding (Pierce et al. 2012) and may increase the frequency of hypoxic events in the Bay.

Ocean climate refers to the phase of various cyclical patterns of temperature and upwelling such as ENSO, PDO, and NPGO. These shifts alter regional weather patterns, resulting in significant effects on the estuary arising mainly through changes in runoff and, to a lesser extent, temperature. We discuss effects on estuarine species composition below.

Ocean pH is decreasing, a consequence of the rise in dissolved CO_2. The reduced pH will affect the estuary through mixing of relatively acidic ocean water into the estuary. The principal concern for the ocean is the vulnerability of calcifying organisms such as bivalves (Fabry et al. 2008), although not all organisms are likely to respond strongly to acidification (Hendriks et al. 2010). The effect of acidification within the estuary is complicated by high short-term and small-scale variability: the pH of ocean water is affected by upwelling of acidic water (Feely et al. 2008), and the pH of the estuary is affected by plant production cycles, land drainage, and wastewater discharge, which can be high in dissolved inorganic carbon (Feely et al. 2010, Fuller 2010, Cai et al. 2011). The key uncertainty is whether the overall range of pH in the estuary will shift enough to affect biota. Any persistent decrease in pH is likely to impair calcifying organisms, notably native oysters, which may be sensitive in the larval stages (see the oyster beds case study, appendix 3.1). Other biota may be affected as well, but that effect is likely to be smaller and is less certain than effects on bivalves.

Most estuaries, particularly in developed regions, are net consumers rather than producers of organic matter and therefore sources of CO_2 to the atmosphere (Smith and Hollibaugh 1993), although net metabolism in the San Francisco Estuary overall appears to be nearly balanced (Smith and Hollibaugh 2006). Low and variable pH in Puget Sound was due to a combination of acidification and eutrophication (Feely et al. 2010). The waters of Central San Francisco Bay may behave similarly, although pH in the rest of the estuary may be controlled more by local and watershed processes. Monitoring data from San Pablo Bay to the Delta show no temporal trend in pH, but pH decreases and becomes more variable from west (saltier) to east (fresher), presumably because of the buffering capacity of seawater.

Freshwater Flow, Temperature, and Salinity

Delta outflow controls the long-term salinity distribution (Science Foundation chapter 2). It also directly affects the estuary by supplying organic matter, nutrients, and organisms from the Central Valley watershed to the estuary. 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 (see the longfin smelt case study, appendix 3.1). Therefore reductions in springtime freshwater flow can be expected to reduce abundance of these fishes both in the open waters and within the marshes.

The supply of materials such as nutrients and organisms from the rivers is important to the estuarine foodweb and helps to supplement a depression in summer-fall phytoplankton productivity at intermediate salinity (Kimmerer and Thompson 2014). However, the magnitude of this subsidy is unknown, and the likely direct impact of the projected changes in Delta outflow seem small since summer-fall is usually a low-flow period anyway. The link between any change in this foodweb subsidy and the Baylands therefore seems rather weak.

Temperature of the Bay's waters has a spatial gradient that reverses seasonally and interannually. Temperature fluctuation near the Golden Gate is dampened by cool summer climate and low seasonal variability in the ocean (Kimmerer 2004). Air temperature in the Central Valley fluctuates seasonally much more than along the coast, and water temperature follows suit. Thus, the estuary is warmest in the Delta during summer (annual range 10-22 °C at Rio Vista), and warmest at the Golden Gate (annual range 12-15 °C) during winter. Freshwater flow has only a minor effect on water temperature in the estuary (Kimmerer 2004, Wagner et al. 2011).

Projections of water temperature under climate scenarios 1-4 were provided only for the Delta because of the known sensitivity of the endangered delta smelt to temperature above 25°C (see the delta smelt case study, appendix 3.1; Cloern et al. 2007). The number of days of temperatures above 25°C at Rio Vista is projected to increase from zero during the historical period of 1984-1999 to ~100 days per year by 2090 under a business-as-usual scenario (Intergovernmental Panel on Climate Change scenario GFDL-A2) and ~18-20 days per year under the more optimistic PCM-B1 scenario (Cloern et al. 2007, Wagner et al. 2011). The increase in projected maximum summer temperature by the end of this century is about 6 and 3 °C respectively under the two scenarios, and increases in projected winter temperature are about half that much (Wagner et al. 2011). This trend is sharply reduced to the west of the Delta as far as Carquinez Strait (Wagner et al. 2011) and presumably even more reduced in San Pablo and San Francisco Bays.

The daily-averaged horizontal **salinity** distribution of the estuary is controlled largely by Delta outflow, but this control is modulated by bathymetry (previous section, see also Kimmerer et al. 2013). It is important to note that an estuarine salinity gradient is always present from freshwater to seawater, but its position changes with freshwater flow and tides, and it often extends into the Gulf of the Farallones. Shallow regions of the estuary are usually well-mixed vertically, while deeper regions of intermediate salinity can be strongly stratified, with higher salinity at the bottom than at the surface. The position of the winter salinity gradient is governed mainly by storm intensity and frequency, modulated by the extent of water storage in snowpack (decreasing) and reservoirs (probably increasing). The position of the summer salinity gradient is controlled mainly by operations of the large water projects in the Delta and salinity in some parts of the estuary can be affected by local wastewater discharges.

Forecasts for future changes in salinity patterns are complicated by uncertainties about future water management and the future physical configuration of the estuary (see salinity discussion, Science Foundation chapter 2). Winter salinity patterns may be more variable between and within years if storms become more intense, but this is difficult to predict and would be altered by levee failures in the Delta. Salinity is likely to penetrate further and more persistently into the estuary during the dry season, a consequence of reduced spring-summer runoff, altered structures and operations of Central Valley water projects to conserve water for human use in summer, an increase in tidally linked areas due to restoration and levee failures, and higher sea level. Without a major change in bathymetry or tidal prism, further salinity penetration in summer will mean that the extent of the tidal freshwater reach in the Delta will shrink while the extent of saline water > 20) in the Bay will expand.

Salinity has numerous effects on estuarine physics, chemistry, and biota. Physical and chemical effects are discussed in Science Foundation Chapter 2. Pelagic organisms move with the water and are not greatly affected by changes in salinity, although their distributions move as the salinity field moves. Benthic organisms and attached plants (SAV and marsh plants) can be strongly affected by the salinity distribution, dying back in areas where salinity has become unsuitable and colonizing newly suitable areas. These changes can be rapid, as in the case of native oysters (see oyster bed case study, appendix 3.1) which died back following high-flow periods in 2006 and 2011 and subsequently recolonized areas in northern Central Bay. Eastern oysters have thrived in reduced salinity because it provided a refuge from less tolerant disease organisms (Hoffmann et al. 2009, Levinton et al. 2011).

Die-backs of eelgrass and possibly other organisms during winter may affect Baylands through long-term shifts in distribution and accompanying shifts in sediment trapping capacity. Higher average salinity in the future may allow eelgrass, native oysters, and other salt-tolerant benthic or marsh organisms to colonize further up the estuary.

Extreme Events

Under the storm scenario (New Understanding: the Baylands and Climate Change, Appendix D), extreme winter flow combined with sea level elevated by the long-term trend combined with an El Niño would cause extensive flooding and drive the salinity field far to seaward of its usual winter position. The spring 1986 flood, upon which this scenario was based, kept Suisun Bay fresh for about two months. With higher sea level at the Golden Gate the response of salinity to flow would be somewhat reduced. The principal effect through the Bay Connection would be this suppression of salinity, which would cause temporary die-backs of some species and range extensions of freshwater species as discussed in the previous section, and could set up conditions favorable for invasive species to establish, as may have been the case with the clam *Potamocorbula amurensis* (see the plankton case study, appendix 3.1).

A winter flood could also have lasting consequences through rearrangements of the sediment distribution (Science Foundation Chapter 2) or if flooding breached levees in the Delta or Suisun Marsh and reconnected present-day lands to the estuary, and a decision were made not to repair the breaches. Such a decision seems more likely in the event of massive levee failures resulting from an earthquake, because repair would take considerable time and may not be feasible for all levees (Mount and Twiss 2005). Over the time scale of a century, these events have a high probability of occurring, but the probability of a permanent response in the estuarine biota that affects the Baylands is highly uncertain.

Warming Effects on Biota

Water temperature affects estuarine biota in several ways, which will vary seasonally and spatially, because of the gradient in temperature discussed above. Temperature sets the biochemical rates that determine the physiology of most estuarine organisms. Increasing temperature will generally increase metabolic rates, except for species near their upper thermal limits which will begin to suffer ill effects. The likelihood of such effects increases with distance into the estuary because of the moderating effect of cool coastal conditions (see Temperature, above). However, there may be some capacity for populations to adapt to altered temperatures.

Rising temperature may stimulate an increase in incidence of disease and parasite attack, although there are almost no data on current levels in any estuarine organisms (but see Friedman et al. 2005 for native oysters). Blooms of the freshwater microalga *Microcystis* occur in the Delta during warm, dry summers and may increase in duration with warming. Higher winter temperatures or a shorter winter season may affect phenology or reproductive success of some species, and provide more favorable conditions for species intolerant of low temperature, although winter temperatures in the estuary are already mild.

Ecological interactions (discussed further below) will amplify the species-specific responses to temperature which will make changes in the ecosystem difficult to predict. These may include changes in phenology that put organisms out of phase seasonally with their food or predators, and changes in frequency or severity of outbreaks of disease or parasites. Overall we can expect some species to be extirpated, some to decrease in abundance, others to increase, others to change seasonal patterns, and still others to extend their ranges into the estuary and become established. The outcome will be an unpredictable shift in the composition of the estuarine biota.

A few species may already be near their upper thermal limits and further increases are likely to prove harmful. In particular, high summer temperature in the Delta will add to the problems already besetting delta smelt, although the link to Baylands is weak (see the delta smelt case study, appendix 3.1).

High summer air temperature, stronger wind, and a greater tidal range may increase the risk of desiccation in intertidal areas (see the rocky intertidal organisms case study, appendix 3.1). Rising sea level is likely to shift the distributions of intertidal organisms higher where space is available, but should not alter the risk of desiccation since the entire assemblage would presumably maintain its position relative to the tidal range.

Remote changes refer to events happening remotely from the estuary that influence the estuary through migratory biota. Such effects are particularly likely for birds that spend summers in the Arctic (Science Foundation chapter 5) and for salmon which will encounter increases in river temperature and reduced summer flow rates. In particular, high water temperature 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, appendix 3.1). 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.

Estuarine Productivity

Productivity of estuarine waters depends largely on phytoplankton (microalgae) rather than external sources such as rivers or marshes (see the plankton case study, appendix 3.1). Benthic microalgae may be an important source in shallow areas but their contribution to estuarine productivity has not been studied. SAV beds are an important source of organic matter locally, but their limited extent constrains their contribution to overall estuarine productivity (see the SAV case study, appendix 3.1). Therefore the key controls on phytoplankton set important limits to estuarine productivity. These controls are light, nutrients, and grazing by clams and zooplankton. Similar controls, plus availability of suitable sediment, limit the productivity of benthic microalgae and SAV beds. All of these controls are likely to have trends through time (see the plankton case study, appendix 3.1).

Light available to phytoplankton is a function of sunlight, water depth, and turbidity of the water. Mean depth of the estuary is expected to continue increasing with rising sea level and erosion. However, the main control on light availability is turbidity, a function of suspended sediment concentration (see above). Turbidity has been the key factor preventing the estuary from becoming eutrophic, i.e., productive enough to cause problems with low oxygen and nuisance blooms of algae. There is concern that some parts of the estuary may become eutrophic once turbidity decreases through reduction of net availability of sediment. This trend could be offset to some extent through nutrient sequestration in marshes if the total area of marshes increases.

Nutrient loading increases with human population size, but loading of some nutrients may be reduced, despite population growth, because of upgrades to water treatment plants. Since the estuary is already nutrient-rich, the overall reduction will mainly limit the maximum biomass of phytoplankton blooms in South to San Pablo Bays, and possibly growth of SAV, its epiphytes, and macroalgae. Reduction in ammonium loading may allow for higher phytoplankton production in Suisun Bay (Dugdale et al. 2007), but the likely magnitude of such an increase is controversial because of other strong controls on phytoplankton production, notably grazing by clams and microzooplankton (Kimmerer and Thompson 2014).

Grazing by clams has imposed a severe limit on phytoplankton biomass in Suisun Bay since the arrival of *Potamocorbula amurensis* in 1987. Species composition of the phytoplankton in the northern estuary has shifted toward smaller forms and more toxic or less nutritious forms (see the plankton case study, appendix 3.1).

Phytoplankton biomass (as chlorophyll) has increased markedly in South Bay over the last 15 years, presumably because of a reduction in grazing by clams. This decrease was attributed to a shift in the ocean climate, resulting in a shift in the species composition of the predators in the coastal ocean and a consequent increase in predation on clams (see the plankton case study, appendix 3.1).

Species Composition

Species composition of estuarine flora and fauna varies as a function of the salinity and depth distribution, seasonal patterns of abundance, and interactions among species. Species composition is likely to change in ways that influence the Bay Connection (see case studies for all estuarine species, appendix 3.1). This change can arise through four mechanisms. First, new species will almost certainly be introduced either accidentally or deliberately. Second, new species may enter the estuary through range expansion that occurs with changing conditions in the ocean or in remote habitats (see previous section). Third, habitat suitability for different species within the estuary may change through any of the mechanisms discussed above, to the extent that species are extirpated or their abundance or ranges within the estuary are altered. Finally, interactions among species are likely to cause long-term changes in species composition (see below). These changes could be catastrophic or beneficial, and may or may not affect the Bay connection; furthermore, most of the changes are unpredictable.

Disruptive **species introductions** in the past provide excellent case studies for projecting future trajectories of change resulting in and from changes in species composition. The San Francisco Estuary is known for the high level of introduced species in its flora and fauna. Two aspects of species introductions are relevant here. First, the invasion event can disrupt the extant ecosystem as described in two examples below. Second, established introduced species become part of the estuarine ecosystem, but their resource use may come at the expense of native species. Although some introduced species are favored for their value in fisheries (striped bass, largemouth bass) and other human activities, there is also considerable interest in protecting and maintaining some native species, notably cordgrass, eelgrass, oyster habitats and delta and longfin smelt (see case studies, appendix 3.1).

The best-studied introduction event was that of the "overbite" clam *Potamocorbula amurensis*, which has caused suppression of phytoplankton and zooplankton from San Pablo Bay to the western Delta since 1987 (see the plankton case study, appendix 3.1). Although variable salinity patterns likely fostered the settlement of this clam (Nichols et al. 1990), its source was most likely ballast water, and such introductions can generally be seen as chance events. This event has reverberated through the foodweb of the northern estuary, where numerous populations of fish are in a state of decline, to which the chronically low abundance of food is a likely contributing factor (Sommer et al. 2007).

Another disruptive introduction was the Brazilian waterweed *Egeria densa*, which spread throughout the freshwater regions of the Delta in the 1990s (SAV case study, appendix 3.1). This species provides habitat for a host of non-native fishes and other species, and effectively excludes native species of fish and other SAV. Its spread is the principal reason why the Delta is now a favored spot for tournament fishing on largemouth bass, an introduced predator. Although *E. densa* is not abundant west of the Delta, its effects on the estuarine foodweb are considerable and very likely influence the Bay Connection in Suisun and San Pablo Bays.

Future introductions are likely to have effects of similar magnitude, although generally it is difficult to anticipate what species might arrive here. Key exceptions are quagga and zebra mussels, which are both already established in California reservoirs and are readily transported on trailered boats. Although these are freshwater mussels and therefore unlikely to become very abundant in the Bay, they could have substantial effects through grazing on phytoplankton in the Delta. Under present conditions the Delta subsidizes phytoplankton in Suisun Bay; therefore a loss of productivity in the Delta could have major impacts on Suisun Bay (plankton case study, appendix 3.1). In addition, loss of productivity in the Delta would reduce food available to species such as striped bass, which is abundant throughout the estuary and uses Suisun and other marshes (Matern et al. 2002).

Changes in the geographic range of marine species track changes in the geographic distribution of temperature (Pinsky et al. 2013). This can lead to changes in the composition of marine species at the entrance to the estuary, we are aware of no examples of permanent range extensions into the subtidal waters of the estuary. The influx of predators on clams discussed above was apparently a result of decadal-scale oscillations in ocean climate (Cloern et al. 2007). The recent return of harbor porpoises to the Bay is also a range extension, although the reasons for their return after 65 years' absence are unknown (http://www.ggcetacean.org/Harbor_Porpoise.html). The suite of species that could enter the estuary from the ocean changes with ocean climate on decadal and seasonal scales, so it may be difficult to detect a long-term change in range of these species.

Another mechanism influencing species composition is differential responses of species to changes, especially in temperature and salinity. Rising temperature will affect seasonal patterns, more strongly in inland areas. Seasonal patterns are likely to shift as heat-tolerant species extend their period of high abundance, and heat-intolerant species retreat (if possible) to a winter peak in abundance. These changes will be influenced by shifts in phenology, such as earlier reproduction by species keyed to the spring temperature increase.

Landward shifts in the salinity field of the estuary will affect spatial distributions, more strongly in the summer dry season. As the dry-season salinity field shifts landward, the geographic distribution of these species will also shift. Changes in response to salinity are clearly evident in spatial shifts of various species of pelagic fish and plankton, which maintain positions more in relation to salinity than to geography. The region of overlap in range of the clams *Potamocorbula amurensis* and *Corbicula fluminea* shifts with the limit of tidally-averaged salinity penetration into the estuary (Brown et al. 2014).

Some species with limited geographic distribution may be strongly affected by shifts in salinity. Examples include native oysters, eelgrass, and Pacific herring (see case studies, appendix 3.1). These species require suitable substrate for attachment, bed development, and spawning, respectively, which is most available in and near Central to southern San Pablo Bays, and less so further up the estuary. Increasing salinity penetration may expand the range of eelgrass but the ranges of oysters and herring may not expand because of the lack of substrate. In particular, herring require some dilution of seawater for successful reproduction, and may not be able to expand their range because of the shortage of substrate.

Consequences for the Bay Connection

The result of shifts in species composition within the open waters of the estuary will be a change in the suite of species available for interactions within marshes. This effect will be most prominent in brackish marshes such as Suisun Marsh, where the scope for changes in salinity is the greatest. Presumably some marine species will be able to penetrate further into the estuary and become significant members of the marsh fauna in areas where they are not now abundant.

Estuarine nekton can exert a controlling influence on species composition and processes in marshes through predation on marsh-resident organisms (Kneib 1997). Therefore changes in the species composition of the estuarine nekton could have a substantial effect on ecological processes with the marshes. By the same token, changes within the marshes could lead to greater or lesser use of the marshes by Bay nekton or alter the biological links between marshes and open waters in other ways. The principal mechanisms for such changes will be the net increase in marsh area due to restoration and protection of marshes from erosion (Chapter 2, and changes in species composition within marshes due to introductions or changes in range (Science Foundation chapter 5).

As with estuaries more generally, a key unknown is the extent to which marshes, either in their current state or in a future state of development, support or would support Bay foodwebs through export of organic carbon or organisms. The estuarine foodwebs in Suisun Bay and the Delta are supported largely by local phytoplankton production rather than inputs from rivers and marshes (Sobczak et al. 2002, 2005), and stable isotope studies show that open-water foodwebs gain little organic matter from marshes or nearshore vegetated areas (Grimaldo et al. 2009). At present the area of extant and restored tidal marsh is about 18% of the area of the estuary, both excluding the Delta (Kimmerer 2004). Marshes are much more productive per unit area than open waters, but only a small fraction of that productivity is available to support open-water foodwebs. Thus, under current conditions the limited extent of marshes surrounding the estuary suggests a small contribution to estuarine foodwebs baywide. Increased marsh development may increase the magnitude of that subsidy but its importance remains to be determined. This highlights the need for better information on the Bay Connection and for research to accompany all restoration programs.

Interactions

The above discussion shows the importance of interactions among the links comprising the Bay Connection. Ecological interactions are arguably the least predictable but among the most important mechanisms for changes in species composition in the estuary. These interactions could take many forms, including predation, competition, disease, and parasitism. Examples of such interactions abound in the literature on terrestrial systems, although estuarine examples are harder to find.

A handful of examples from the San Francisco Estuary show the importance of interactions in setting the spatial and seasonal distributions of species, but also in the difficulty of detecting such interactions. The trophic cascade initiated by a shift in ocean conditions, resulting in an increase in phytoplankton biomass in South Bay, is discussed above (see also plankton case study, appendix 3.1).

The introduction of the clam *Potamocorbula amurensis* precipitated a series of events including a decrease in phytoplankton production and a substantial contraction of the salinity range of northern anchovy, which had been the most abundant fish as far up-estuary as Suisun Bay (plankton and anchovy case studies, appendix 3.1). Decreases in spring-summer abundance of several species of copepod and mysid had strong effects on the availability of food for fish, which probably caused a decline in abundance of longfin smelt and striped bass. This complete rearrangement of the trophic links in the brackish parts of the estuary was the most prominent example of a complex network of ecological interactions ever observed in the estuary.

Abundance of *P. amurensis* in San Pablo Bay decreases each fall-winter, apparently because of predation by waterfowl (Poulton et al. 2002). This results in an annual pattern of abundance of the clam, and the possibility of spring phytoplankton blooms occurring before the annual increase in abundance of clams (plankton case study, appendix 3.1). This pattern depends on the continued high consumption rate by the waterfowl, which may be under the control of processes in their distant summer habitats.

A hybrid of native cordgrass with the invasive cordgrass *Spartina alterniflora* has colonized estuarine mudflats throughout saline parts of the bay. Changes in physical and chemical characteristics of the sediment in the colonized areas have led to reductions in survival and abundance of many foodweb organisms that are important to consumers such as birds (Neira et al. 2006).

The interactions discussed above were all associated with rapid changes identified in monitoring programs that included many of the key species involved. Trends in the key drivers of change are likely to be much slower. Thus, ecological interactions are often subtle, complex, difficult to detect or identify, and nearly impossible to predict (Figure 3.1). They will likely amplify or override some of the more direct effects discussed above. Therefore it would be unwise to attempt more than a broad, general forecast of changes in species composition except for the rather straightforward effects of salinity and effects on individual, well-studied species.

The importance of ecological interactions is illustrated in Figure 3.1. Each species responds in its own way to aspects of its physical environment such as temperature, salinity, turbidity, and the available of physical habitat (e.g., water depth and velocity, sediment availability and type, bathymetric complexity). Each species also interacts with a variety of other species where they overlap in time and space. Interactions include consumption of one species by another, providing an energy source to the consumer or parasite but imposing mortality on the prey, which can also impose constraints on prey behavior and selective pressure on prey attributes such as size at maturity.

INFORMATION NEEDS AND KEY UNKNOWNS

Key information needs for the Bay Connection were identified in the SHGR. The fundamental unknowns for identifying, forecasting, and responding to changes in the Bay arise from uncertainties in the drivers, which are discussed in Chapter 1 and 2.

Some unknowns could be reduced to clarify and anticipate the likely response of the estuary to long-term change. The specific characteristics of exchange between marshes and open waters are key to understanding the Bay Connection, but are very poorly understood. For example, we have no estimates of organic matter leaving marshes anywhere in the system. Except for a study showing net consumption of mysids in the China Camp marsh (Dean et al. 2005), we do not know the sign or magnitude of the fluxes of phytoplankton or zooplankton between marshes and open water. We do not know how important the

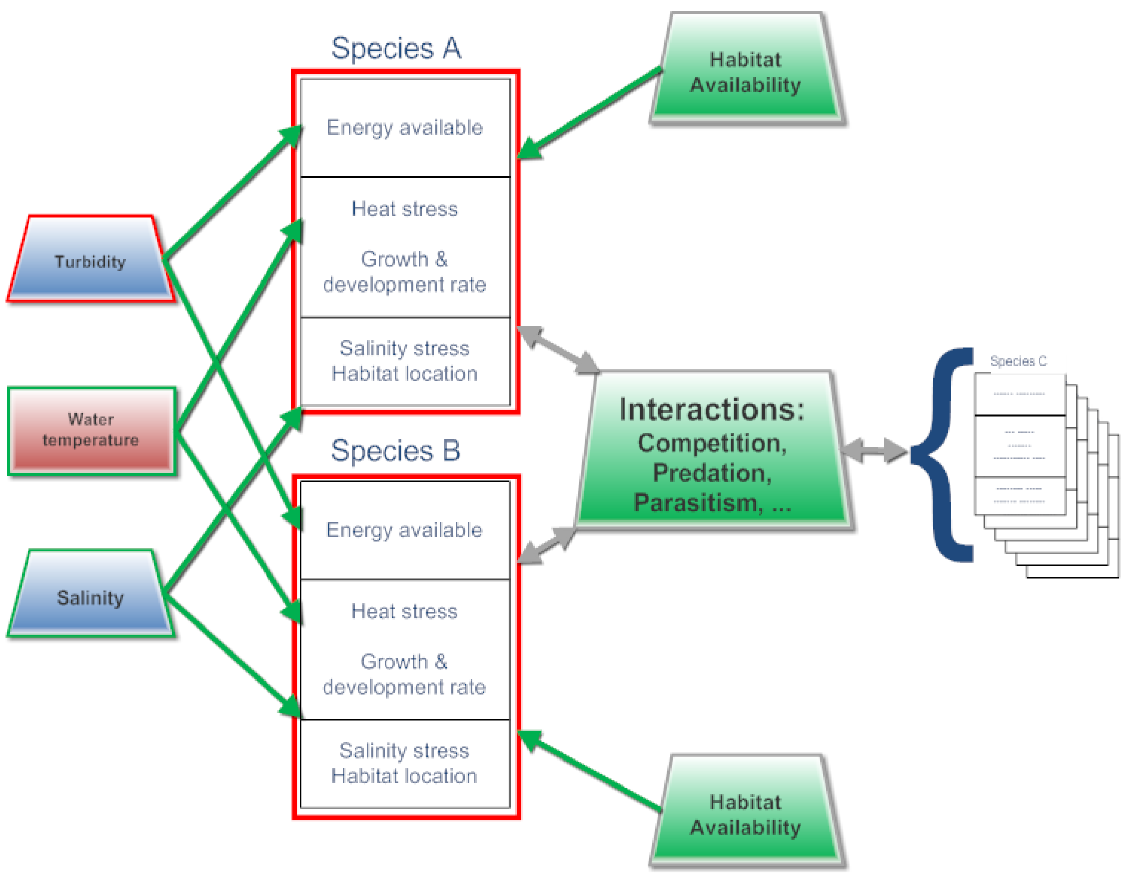

Figure 3.1. Simple representation of ecological interactions and how they effect local abundance of a species.

marshes are to the populations of fish and crustaceans that use them, or the extent to which organic matter produced in the marshes is carried out into the Bay by nekton. These all point to a program of investigations to determine these fluxes and how they may change in the future.

Understanding of the ecology of the San Francisco Estuary has benefited from data provided by two long-term monitoring programs that measure phytoplankton biomass and basic water quality (temperature, salinity, dissolved oxygen, various measures of turbidity). The Interagency Ecological Program (IEP) samples monthly for these variables from the Delta to San Pablo Bay. The US Geological Survey (USGS) monitors monthly in the channels from South Bay to Rio Vista in the western Delta. Both programs maintain continuous monitoring stations that measure temperature, conductivity (salinity), and in some cases dissolved oxygen, suspended sediment concentrations, and other variables. The IEP also samples monthly for zooplankton and macrobenthos at many of the stations sampled for phytoplankton. Fish and other nekton are sampled by several programs, most of which emphasize the Delta and Suisun Bay. The IEP's San Francisco Bay Study samples for nekton throughout the estuary although with limited coverage of the Delta. The data produced by these programs have been critical for investigating causes of declines in fish abundance and other changes (e.g., Thomson et al. 2010, Mac Nally et al. 2011). Finally, the Regional Monitoring Program (RMP) samples throughout the estuary semiannually for contaminants and benthos (Anderson et al. 2007).

Despite this extensive monitoring, substantial gaps exist in the information available to support decision-making. None of these monitoring efforts samples for zooplankton in Central and South Bay, despite their key role in estuarine foodwebs. Sampling for benthos is inadequate to detect trends in abundance or to provide estimates of grazing rates on the overlying phytoplankton, particularly in Central and South Bay. Sampling for phytoplankton includes taxonomic composition but biomass estimates include only bulk chlorophyll, and there is no sampling at all for microzooplankton, which at times are the predominant grazers on phytoplankton. There is no monitoring program that adequately samples jellyfish, which may have increased in harbors in the estuary and perhaps also in open waters with potentially large effects on the estuarine plankton (Mills and Rees 2000). Most of the monitoring focuses on abundance and species composition, and there is no monitoring of vital rates, which would be essential for identifying trends in response to temperature or ecological effects.

IEP monitoring is mandated by the State Water Board, has a funding stream, and is likely to persist, although efforts to expand the scope of the zooplankton program in 1997-1999 did not go beyond the pilot stage. The USGS monitoring program is not mandated, despite its immense value in tracking and understanding changes in phytoplankton and water quality within the estuary, and the publication of ~100 papers, some very influential, using data collected in this study.

It is important to note that monitoring is essential for detecting trends and changes, but monitoring is insufficient to determine cause-effect relationships or linkages within the ecosystem. Therefore, even if the gaps in monitoring were to be filled, our understanding of system structure and function would be inadequate without a research program targeted at the key unknowns.

ADAPTATION

Although the high level of uncertainty makes planning difficult, the Bay Connection offers some opportunities for adaptation to long-term change. The Subtidal Habitat Goals Report (SHGR 2010) discussed connections between Baylands and the subtidal realm, and expressed a preference for integrated restoration driven by the strong links between them in terms of water, sediment, organic matter, biogeochemical processes, and organisms. Most of the habitat restoration projects implemented in and around San Francisco Bay in the last 40 years have focused on single habitat types such as marshes and riparian zones. Many ecosystem processes occur at a larger scale than individual habitats, as discussed earlier in this chapter. A few large regional restoration projects have incorporated planning for multiple habitats across landscapes, including the South Bay Salt Pond Restoration Project and the Sears Point Restoration Project. Integrating restoration between subtidal and nearby marsh and upland habitats may provide ecological benefits, and the resulting interactions may result in cost savings compared to equivalent isolated restoration projects.

The most promising approach is for subtidal and intertidal restoration that results in protection of valuable Baylands. The SHGR identified several approaches to adaptation to long-term change, in particular for ways to protect marshes and other valued intertidal areas against erosion. Restoration is often expensive, uncertain, and difficult; therefore it seems logical to design restoration to capitalize on links between nearby habitats. Subtidal habitats that increase bottom friction, mainly oyster reefs and eelgrass beds, could be placed so as to attenuate wind waves and thereby buffer tidal wetlands and creek mouths from erosion. The combination of marsh restoration and nearshore 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. An additional advantage to integrated restoration is to reduce the effects of habitat fragmentation. Extant marshes are small and geographically dispersed. Even after completion of the Baylands Goals Project, these habitats will not approach the extent and contiguity of pre-settlement marshes. Yet, as discussed earlier in this chapter, connectivity among habitat elements is a key feature of ecological landscapes.

Adaptation strategies will vary depending our goal: whether we are trying to increase the resiliency of existing subtidal habitat, create or expand new areas of subtidal habitats, and if we are incorporating subtidal habitat into larger efforts of nature-based adaptation of the shoreline. There are opportunities to conduct pilot projects to assess the integration of subtidal habitats into multi-objective Baylands projects to achieve multiple goals. Multi-objective and multi-habitat project designs may maximize cumulative benefits for climate change adaptation. The use of combined approaches in-lieu of a single strategy, such as sea wall construction, allows for better preparation for a highly uncertain and dynamic environment; but few projects have examined the interactive and synergistic effects and benefits of combined approaches to adaptation (Cheong et al 2012). One protection type alone can fail, and by integrating and "layering" habitat types we may create a toolbox that is more useful than just one tool alone. By thoughtfully integrating design features that can have both ecosystem service and function benefits, projects can achieve more than one outcome and can increase overall project success by including design components that support each other. The particular type of features, and their scale, dimensions, placement, and height, all must be planned with consideration of existing conditions and with future projected changes to bathymetry, substrate, tidal height, and water quality conditions. One size does not fit all with most habitat planning and restoration projects and this is especially true with constructing adaptive features.

A key component inherent in adaptation is allowing for and encouraging thoughtful and science-based experimentation in climate change restoration designs. Restoration techniques for subtidal and open bay habitats are lesser understood than for baylands, which points to the need for a thoughtful, phased approach of experimental pilot projects that can help address key science questions and generate site-specific data on restoration outcomes. Timing is critical and pushes the need to start implementing pilot, experimental integrated projects as early as possible so that we can better understand cumulative values from linking restoration design goals and outcomes of multiple habitats in one area. Recommendations of the Intergovernmental Panel on Climate Change (IPCC), State of California Climate Adaptation Plan, and many other global and national climate change recommendations focus on the urgency of getting started as early as possible in order to pilot and test adaptation actions. In 2010 the US, Australia, and other countries committed to financially kick-starting mitigation and adaptation initiatives to produce lessons for future climate change investments and larger-scale projects (2009 Global Climate Conference).

The California Coastal Conservancy and other regional agencies are promoting project with multiple objectives of safeguarding both people and wildlife by using nature-based solutions that provide co-benefits for people, wildlife, and the economy (Coastal Conservancy 2012, Point Blue 2013). These agencies promote on-the-ground demonstration projects that implement innovative approaches or enhance understanding of effective management strategies and will potentially lead to broader change to policies, regulations, or to duplicating the effort elsewhere. Guiding principles in adaptation implementation include conserving and restoring landscape linkages and connectivity areas that will allow diverse species to move to new locations and will enhance overall species persistence (Resources Legacy Fund 2012).

INTRODUCTION TO THE RECOMMENDED ACTIONS

Strategies for Resilience

Resilience management goes beyond risk management to address the complexities of large integrated systems and the uncertainty of future threats from climate change (Linkor et al 2014). Future planning should conserve and create subtidal habitats as an integral part of the aquatic transition and adjacent Bay ecosystem. Subtidal habitat is an important component of the landscape vision for the Baylands over the next century, and these habitats provide ecological benefits to the Baylands by supporting wildlife and by providing physical protection to adjacent intertidal areas. There are opportunities for thoughtful experimentation with integration of subtidal habitats into multi-objective Baylands-Open Bay pilot projects designed to achieve multiple goals. As described earlier, climate changes will influence sea level, salinity, temperature, and storm, sedimentation, and flow regimes, etc. that affect the health and function of subtidal and intertidal seabed in San Francisco Bay. This chapter has discussed the physical and biological connections between offshore shoals, the open bay waters, and the baylands; and the subtidal-intertidal transition zone in many shoreline segments provides us with an area to pilot new ideas and thoughtfully test new approaches and methods for protection of intertidal shorelines and tidal marshes. Integrated physical and biological goals can be better aligned upfront into adaptive designs that enhance and reinforce the ecosystem functions and services in the Bay Connection.

There is specific, increasing interest in designs that use the restoration of natural habitats to achieve physical benefits as well. These approaches have been coined "green infrastructure", "soft shorelines", "living shorelines", etc. (see Science Foundation chapter 2. The baylands-shoreline-subtidal edge is increasingly important in planning for adaptation measures to address sea level rise and climate change. As the New York State region looks to become more resilient in the face of future storms like Hurricane Sandy, in Staten Island, planners are looking to the ecological past, which included substantial offshore oyster reefs, to define approaches for the future. A living breakwater project designed by SCAPE Landscape Architects was among the winning projects for the Department of Housing and Urban Development's Rebuild by Design contest, and the state will receive $60 million from HUD to implement it along the South Shore coast (Orff et al 2014, www.scapestudio.com).

"Living Shorelines" designs can span across intertidal and subtidal areas and can take many forms, but they are generally accomplished via the strategic placement of biological habitat features (marshes, eelgrass beds, oyster beds, mudflats, etc.) and other materials (rock groins, sand beaches, shell mounds, berm islands, high tide islands, etc.) that absorb and reduce the energy of waves and currents, thereby protecting intertidal landforms (http://www.habitat.noaa.gov/restoration/techniques/livingshorelines.html). The features each have particular values and benefits for different species, and have the potential to provide ecosystem services such as wave attenuation and sediment accretion that may help reduce impacts to the baylands from stressors like sea level rise and increased storm frequency. The approach also can enhance valuable ecosystem functions such as nesting, feeding, and high tide refugia by adding habitat structure, increasing habitat availability of particular substrates at certain tidal heights that benefit specific species, creating linkages between habitat types, and generating substantial food resources for a variety of birds, fish, and wildlife that use the Bay Connection.

Some living shorelines projects are still based on somewhat traditional hard structure (massive amounts of granite, rock, breakwaters, etc.) that then have limited habitat components incorporated into the design or expected outcomes. Some of these efforts have been criticized for lack of ecosystem connectivity components and lack of monitoring (Pilkey et al 2012). While pilot projects in San Francisco Bay are also testing the use of artificial structures and hybrid approaches, there is a targeted approach to better define what the living shorelines concept means in this system- including careful and thoughtful use of fill, integrating multiple habitats and habitat connectivity into the design goals and outcomes, and setting co-equal goals of increasing both physical and biological benefits through careful monitoring and assessment.

Multi-objective and multi-habitat project designs may maximize cumulative benefits for climate change adaptation. By thoughtfully integrating design features that can have both habitat restoration and physical protection benefits, projects can achieve more than one outcome and can increase overall project success by including design components that support each other. For example, eelgrass beds offshore from a marsh may help provide a variety of benefits: attenuating waves (Koch 2001), providing food resources for waterfowl, providing a healthy native substrate for Pacific herring spawning (CDFW Annual herring surveys: https://www.dfg.ca.gov/marine/herring/seasonsummaries.asp), and functioning as a habitat corridor for fish and salmonids as they move between the open bay and the baylands (www.sfbaylivingshorelines.org, Oct 2013 Monitoring Report). Oyster reefs designed as living breakwaters may have the potential to keep pace with sea level rise (Rodriguez et al 2013). Oyster beds offshore may provide these same benefits, and placement of shell reefs near to eelgrass beds may improve the success of both efforts- oyster filtering can improve turbidity which can help improve light attenuation needed for eelgrass growth (Oct 2013 LSP). Marine vegetated habitats (seagrasses, salt marshes, macroalgae, and mangroves) occupy .2% of the ocean surface but contribute to 50% of carbon burial in marine sediments. Canopies dissipate wave energy and high burial rates raise the sea floor, buffering the impacts of rising sea level and wave action that are associated with climate change (Duarte et al 2012). Like eelgrass beds, macroalgal beds provide both physical habitat and food for numerous organisms, and they can also alter flow fields, providing small organisms with shelter from currents and predators, and can trap sediment, alter sediment chemistry, and provide a substrate for spawning (Subtidal Habitat Goals Report, State Coastal Conservancy 2010). The wrack produced by eelgrass and macroalgae is an important food source for invertebrates living interstitially on beaches, mudflats, and marshes. These invertebrates in turn provide a food source for shorebirds and many other species along the shoreline and lower edges of tidal wetlands. Restoration of multiple habitat types adjacent to one another can provide benefits that may help facilitate successful restoration of each single habitat type, and achieve greater cumulative results.

Restoring adjacent habitat types with different benefits may support the various dynamics of the bay connection, and result in higher overall ecosystem functioning of the baylands and physical protection at the same time. This type of thoughtfully integrated design planning can greatly increase cost-effectiveness, by designing efficiencies into multi-objective projects that result in "low or no-regrets" restoration- ie achieving habitat restoration benefits while experimentally testing new approaches to climate change adaptation.

Because there are multiple data gaps and unknowns, it is imperative that adaptation proceed with a phased, experimental approach in order to learn what methods will be successful.

Link to the Subtidal Goals Recommendations – Integrated Habitats and Living Shorelines

The SHGR identified several approaches to adaptation to long-term change, in particular for ways to protect marshes and other valued intertidal areas against erosion. As mentioned, one offshore/onshore adaptation technique in the pilot phases of experimentation in San Francisco Bay is the concept of living shorelines. The approaches can vary and can utilize a diverse suite of habitat restoration techniques from subtidal to upland at different elevation and tidal heights to restore, enhance, and create natural habitat for species that use the Bay Connection (including salmonids, sturgeon, sharks, herring, striped bass, rockfishes, anchovies, sardines, bottom fish, etc.).

Design Features will Vary According to Site Conditions

One size does not fit all with most habitat planning and restoration projects, and this is especially true with constructing living shorelines as adaptive features. The effect or benefits obtained relate directly to site conditions and the type of habitat features and methods used. The particular type of features, and their scale, dimensions, placement, and height, all must be planned with consideration of existing conditions and with future projected changes to bathymetry, substrate, tidal height, and water quality conditions. For example, one meter tall oyster reefs may provide substantial wave attenuation at a shallow site but would not have any effects on wave heights if placed in deeper water at the Golden Gate. Species tolerances must be factored in as well.

Some sites with broad shallows may lend themselves to horizontal levees, eelgrass beds, oyster beds, sand beaches, etc. Steeper sites may have limited options, as depth and slope play a large role in both wave attenuation and habitat suitability for particular species. A variety of site conditions in San Francisco Bay will require a variety of approaches, with some steep, high-wave-action sites still requiring traditional hard structures like seawalls and breakwaters for protection. There is an opportunity to explore "hybrid" designs, modified approaches such as using oyster shell to create living breakwaters, or varying materials and orientations on seawalls to support algal and invertebrate habitat. These kinds of innovative techniques should be explored, in order to maximize habitat values at the bay connection and related physical conditions of the baylands and the urban edge.

Pilot Project Examples

Current living shorelines pilot projects in San Francisco Bay are testing the use of eelgrass beds, native oyster reefs, artificial reef structures, woody debris, re-graded low marsh shorelines, and restored sand beaches and coarse gravel beaches. Preliminary data from the projects show substantial success in achieving multiple objectives- some examples include:

San Francisco Bay Living Shorelines Project: a one-acre eelgrass and oyster reef restoration project constructed in July 2012 at -1' MLLW has had more than two million native oysters settle in the first year, and an increase of more than ten new species using the site including bay shrimp, crabs, white sturgeon, steelhead, bay gobies, black oystercatchers, wading birds, and others. Up to 25% of the oysters are reproducing, along with shrimp, Dungeness crabs, nudibranchs, and bay gobies. There has been a significant increase in foraging wading birds at the site, indicating an increase in fish prey. The oyster reef structures reduce wave energy by 30-50%, depending on the water levels, with the strongest effect at mean tides (www.sfbaylivingshorelines.org, Monitoring Report October 2013).

Arambaru Island Restoration Project: The re-contouring of this marsh island has reduced erosion and created haul-out areas for harbor seals and roosting areas for shorebirds and other wildlife. Placement of rock, gravel, and woody debris has helped to create roughness that slows wave action (www.richardsonbayaudubon.org).

Adaptation Recommendations

Adaptation within the Bay Connection should include methods to anticipate and respond to changes that are likely to occur over the long term, and pilot experimental demonstration projects to test ideas and gather data on results that could be scaled up. Several adaptation approaches should be tested to address specific stressors and improve the overall health of the bay connection and the Baylands.

These might include:

- Develop integrated restoration approaches that have sound experimental designs with a careful eye towards sediment dynamics, water flow, and physical and biological benefits.

- Integrated project designs that include multiple habitats and multiple objectives should be tested and can achieve cumulative benefits. Project design objectives should include both biological and physical goals when possible.

- Attention should be paid to both ecosystem services and ecosystem functions when planning specific habitat features.

- Pilot multi-objective, experimental subtidal restoration projects to assess whether these approaches can protect adjacent marshes and enhance the bay connection through increased food and habitat resources.

- Experimental projects should test a variety of designs in a variety of site conditions to learn what can work and at what scales.

- Share results broadly with resource agency staff, academic agencies, and consultants so that similar projects can get initiated at additional sites and so information can inform scaled-up efforts.

- Acquire land to act as buffer zones, e.g., around streams that provide significant sediment to the Bay or provide habitat for anadromous fish.

- Acquire or cause abandonment of islands in the Delta and Suisun Marsh that are particularly vulnerable to flooding. Some of the islands in these regions would, if flooded, cause a substantial increase in area inundated by tides, thereby increasing salinity penetration and altering tidal heights in other areas. The vulnerability of these islands introduces uncertainty about future conditions that could be reduced by selective flooding or strengthening of levees.

- Establish a program to anticipate and prepare for the consequences of the impending invasion by quagga and zebra mussels. This would go beyond existing efforts to slow the spread of these species by the California Department of Fish and Wildlife (CDFW; http://www.dfg.ca.gov/invasives/quaggamussel/)

- Finalize and implement the draft rapid-response plan in the CDFW's Invasive Species Management Plan (2008; https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=3868, accessed 24 March 2014) for identifying and attempting to eradicate newly introduced species, and expand it to include estuarine species.

SUMMARY

The most important changes expected in the Bay Connection are those with the highest likelihood and biggest impact on the Baylands:

- Changes in the sediment budget (addressed mainly in Science Chapter 2.

- Changes in the salinity distribution arising from a variety of causes (see Science Chapter 2).

- Shifts in species composition in all habitats (due to introductions) and range shifts (due to changes in temperature and salinity), together with the ensuing (but generally unpredictable) ecological reorganization.

- Continuing increase in water clarity with increasing potential for large phytoplankton blooms and eventual eutrophication, and possibly expansion of harmful algal blooms.

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