Science Foundation Chapter 5
Risks from Future Change for Wildlife

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INTRODUCTION

Chapter Orientation

Recommendations for effective management actions require in-depth and integrated understanding of climate change impacts on wildlife. In this chapter, we include species of both plants and animals as 'wildlife.' Here we address two over-arching questions:

- How will populations of plants and animals in bayland habitats be affected by climate change?
- Which management actions can be most effective in keeping populations healthy and/or restoring population health, given anticipated climate change impacts?

Climate change is not a new form of stress but an intensification of impacts wildlife have suffered from human use since the Gold Rush: habitat loss and fragmentation, impaired ecological processes associated with land and water use, invasive and pest species, reduced and isolated populations, reduced population fecundity, reduced dispersal opportunities, etc. For both human populations and wildlife, many of the

greatest impacts of climate change will occur suddenly rather than gradually – storm surges that overtop levees and inundate human infrastructure will simultaneously have disastrous effects on wildlife. Wildlife protection must address both the long term trends in stresses and the sudden catastrophic events.
We emphasize the dynamic nature of the environment for wildlife – past, present, and future – as well as the functioning of wildlife within the changing environment. All wildlife in the San Francisco Estuary have evolved to accommodate environmental change. In the past millennium there have been strong fluctuations in salinity and in rates of sea-level rise, (see Science Foundation Chapter 2). The difference now is the multitude of stressors on wildlife and the impaired ability of wildlife populations to respond to these stresses. For instance, housing developments in areas adjacent to intertidal habitat eliminate refuge habitats during times of high water and thereby promote excessive predation on marsh wildlife. Therefore, in this chapter we consider how resilience of wildlife to climate change and other stressors can be maintained and enhanced. With climate change and other changes in land-use, the landscape – that is the mosaic of habitats in the San Francisco Estuary – will change and organisms must respond to that change. In many cases, a species can thrive only if it is able to move, to colonize new habitat, or re-colonize areas formerly occupied. Therefore we emphasize management actions that promote successful dispersal and recruitment into new areas, in addition to promoting persistence in areas currently inhabited. In this way, actions that maximize resilience are most likely to be effective.

A healthy baylands ecosystem is characterized by heterogeneity rather than uniformity. A mosaic of habitat patches allows an array of species to persist, but only if the mosaic components are functionally connected. Plants and animals must be able to successfully move from one patch to another, at short (e.g., daily) or long (annual, decadal) time scales. The goal is a landscape that is dynamic and responsive; flexible, rather than static. The desired landscape is one that changes with time in a way that maximizes the long-term persistence of wildlife populations in the face of climate change. The original Bayland Goals Report (1999) was primarily concerned with targeting maps to achieve a mix of habitats in an estuary in which many important habitat types were missing or under-represented. This 2015 update for climate change emphasizes persistence of plants and animals in areas currently inhabited, as well as successful dispersal and recruitment into new areas, many of which did not exist in 1999.

Approach

We emphasize **population-level** consequences of climate change on wildlife. That is, climate change effects on long-term **population trends** and **population viability** or **sustainability** of bayland plants and animals. These population trends depend on survival, reproductive success, recruitment and dispersal rates. To understand and address the impacts of climate change on population viability, we focus on **population resilience** – by which we mean how well various species tolerate or recover from changes in the environment. We focus on population-level consequences while also stressing the importance of habitat. Bayland habitats are critical in terms of the plants and animals they support, but habitat change is only one of the impacts of climate change on wildlife. Adequate habitat is a necessary but not sufficient requirement for long-term maintenance of wildlife in the face of climate change.

Survival, reproductive success, recruitment, and dispersal rates are difficult to measure, and even more difficult to predict. We qualitatively describe how climate change will affect these key population processes, based on the insights and predictions we have available. We use a conceptual model and draw on ecological models to describe these processes.

We are concerned with both **migratory animals** and **year-round residents**. For migratory species, survival during their time in baylands may, in some cases, be affected by climate change just as it is for year-round residents. In other cases, climate change effects for migrants in the estuary can alter survival and/or reproductive success elsewhere, i.e., on the breeding, feeding, or wintering grounds. In contrast, for other populations of migratory animals, conditions elsewhere may override any effects of conditions in the estuary.

Our approach integrates diverse **environmental processes** on **population trends and viability**. We use case studies of individual species to describe the effects of drivers on population trends and viability. We briefly describe how those drivers interact. We then look across the case studies for patterns of impacts across species. With that background, we provide a basis for management actions that will enhance population resilience and thereby maintain or restore wildlife populations.

The chapter does not describe all possible ecological effects of climate change on plants and animals, but rather those that can be expected to most affect population maintenance, resilience, etc., and thus require management attention. A change in **phenology** (i.e., the change in timing of important events in the annual cycle), for example, is not by itself deleterious, unless such a change results in increased mortality, decreased reproductive success, etc. In some cases, climate change may lead to a mismatch in timing between a predator and its prey; that may lead to, say, a decrease in body condition, which then may translate into increased mortality or decreased reproductive success. We evaluate the evidence for such impacts and linkages. Similarly, climate change may result in a change in **species co-occurrence** as species alter their habitat use (Ackerly et al. 2012); this may in turn increase competition, predation or disease and, thus, alter survival, reproductive success, recruitment, or dispersal.

Framework

Impacts of climate change will depend on: a) the magnitude of the change in stressor, b) the sensitivity of a species, and c) the resilience of the organism, i.e., its ability to overcome or compensate for change due to stressors. A climate change impact may be of concern because the change is of great magnitude or because of high sensitivity to a change in the stressor. The impact will also depend on resilience of the population, which can depend on the effects of other stressors or the degree to which the population has recovered from previous stressor impacts.

1) **Uncertainty and Risk**

The consequences of climate change for plant and animal species cannot be predicted with certainty. Climate projections themselves show much variability and uncertainty, and new projections are provided regularly, superseding previous projections. We rely on summaries from other workgroups (see Science Foundation Chapters 1, 2, and 3) as well as other recent reviews (e.g., Cayan et al. 2012, Heberger et al. 2012, Ackerly et al. 2012) for these projections. The **consequences**, i.e., the effects of such changes (both positive and negative) for wildlife, add another layer of unpredictability. For example, changes in mean precipitation are difficult to predict for the San Francisco Estuary and its watershed, but what is clear is that precipitation patterns will become more variable (on daily, seasonal, and annual scales); that is, extreme precipitation events will become more common (Cayan et al. 2012), leading to increased probability of droughts and floods. Hence, a probabilistic framework is needed and management approaches must be designed with this unpredictability in mind.

Risk provides a useful concept for this chapter. The National Climate Assessment (Burkett and Davidson 2013) partitions risk into the product of **consequence** and **likelihood**. Consequence reflects **vulnerability to climate change** and other stressors. Likelihood reflects **probability of occurrence**. A severe outcome of low probability can be as much a concern as a moderate outcome with intermediate probability.

This approach, by itself, is well-suited for consideration of infrastructure. However, living systems are much more dynamic. Plants and animals have adapted to environmental change, rather than environmental stasis. The San Francisco Estuary has been especially dynamic, and has changed radically in the past 10,000 years (Parker et al. 2012a). Local extinction and dispersal to, or colonization of, new habitat has occurred repeatedly in the past. What is different now are the cumulative, anthropogenic effects such as (1) habitat fragmentation and alteration, barriers to dispersal (such as freeways, shopping malls), (2) contaminants, and (3) alteration of habitat and foodwebs due to non-native species introductions. Moreover, the rate of climate change anticipated in coming decades is unprecedented. The combination of increased rate of change, greater extreme events, and additional stressors, poses a high risk to wildlife.
We emphasize that living species have some capacity to tolerate or adapt to climate change. It is the combination of increased climatic impacts with ongoing human impacts that threaten wildlife populations. Management actions need to **enhance resilience of plant and animal populations**. In particular, this means reducing mortality on adults and juveniles, increasing reproductive success, ensuring their ability to disperse, while maintaining genetic diversity. Thus, the ability to withstand impacts of climate change depends critically on managing the effects of all stressors. Management actions may be more effective with regard to co-acting stressors, compared to actions that address climate change effects directly.
We emphasize the importance of episodic **extreme events**. The challenge is to consider relatively rare, catastrophic events that have profound long-term consequences (Callaway and Zedler 2004). One extreme event can lead to local extinction, which provides a reason to consider **re-colonization** potential. A site may lose its wildlife population but be suitable to re-colonization. To that end, we require "source" populations in proximity, and facilitate successful dispersal. Current conditions (such as habitat fragmentation, alteration, and contaminants) have already exerted deleterious effects and thus increased vulnerability to climate change.

2) **Case Studies**
The basis of this chapter is a suite of 32 case studies covering a wide variety of plants and animals. Our intent is not to duplicate the extensive case studies published in 2000 for the Goals Report (Goals Project 2000), but rather to update them in three ways, by considering: (1) the likely impacts of climate change, (2) the changes observed for species and information learned since 2000, and (3) specific management recommendations relevant to (1) and (2). We include two first-time case studies, on tidewater goby and grunion, because changed conditions in the estuary, including climate change, may allow these extirpated species to return. Some case studies combine similar species into suites of species that are likely to respond similarly, or for which we do not have enough information to justify separate entries. We refer to select case studies written for the Bay Interface workgroup (Science Foundation Chapter 3), as well as by our own workgroup members; all case studies are available in Appendix 5.1.

The workgroup used three primary criteria and two secondary criteria to choose species.

Primary criteria were:
- Ecological processes and status of the species are well understood
- High conservation concern and/or especially vulnerable to climate change
- Representative of other species.

Secondary criteria were:

- Species or species group especially associated with bayland habitat.
- The species or species group plays an important ecological role (e.g., with regard to foodweb).

Our intent is address threatened and endangered species as we encompass the broader community of bayland plants and animals of concern. The 32 case studies are listed in Table 5.1, with information on broad taxonomic group, sub-category within that group, and habitat.

CONCEPTUAL MODEL

Our conceptual model (Figure 5.1) complements the habitat-focused models presented in Science Foundation Chapters 1, 2 and 4.

For wildlife, we are concerned with two main types of climate change impacts, long-term trends and episodic events. At the top of the figure are three classes of drivers:

1. Trends in ocean conditions, ocean chemistry, tidal range, and sea level. These will produce changes in inundation regime, salinity, and chemical processes in wetlands.

2. Trends in temperature, affecting ocean, runoff patterns, and local conditions. These will change sediment supply, runoff patterns and chemical and biological processes in wetlands.

3. Changes in the intensity, frequency, duration, and/or timing of unpredictable but severe events, especially floods, droughts, and thermal stress, which in turn affect wildlife. These unpredictable events can produce immediate, direct and long-lasting impacts on wildlife populations that increase the risk of extirpation and extinction.

Habitat change is mostly driven by the trends in the first two classes of drivers. Even levee breaks or scarp collapses that suddenly change habitat features are primarily the result of ongoing trends of sea level rise, sediment starvation, etc. On average, plant and animal populations will reflect long-term trends and associated changes in habitat structure and average salinity distributions. But average population size through time is not the best indicator of population viability or sustainability. Extinction risk particularly reflects extreme events, floods, droughts, and storms (Thibault and Brown 2008). Such risk is amplified by smaller and scattered populations that may result from habitat fragmentation and loss. Habitat loss and fragmentation also strongly affect an organism's ability to rebound from the effects of extreme events.

Thus, our conceptual model addresses both gradual and stochastic (i.e., unpredictable) impacts of climate change on wildlife populations, as well as the interactions among the various stressors. These stressors already affect plants and animals—here we elucidate how climate change interacts with additional stressors.

Trends and Episodic Events

Changes in habitat, and its spatial context, are displayed on the left side of Figure 5.1. **Depth** and **elevation** of wetland habitats and the **salinity** and **turbidity** of the overlying aquatic habitats will change in response to long term changes in sea level, sediment flux, etc. Interannual variation in weather will cause such features to change more in some years than others, but overall climate change will affect ongoing trends. These trends in physical parameters will produce corresponding trends in the **size** and **connectivity** of habitats for most species. Habitat quantity, quality, and connectivity are all fundamental drivers with respect to the long-term population trends, abundance, and resilience of every plant and animal species.

Climate change will affect habitat in two ways: (1) configuration of habitat in the larger landscape matrix as reflected in changes in **connectivity** and **size**; (2) suitability of habitat needed to support healthy, resilient populations (e.g., contain suitable nest locations, foraging opportunities, refugia from predators, etc.), which includes **patch configuration**. Changes in habitat will affect not only the ability of populations to persist in an area but in their ability to **colonize** newly suitable habitats or **recolonize** suitable habitats when their populations recover from disasters. Thus, changes in patch configuration will have large impacts on species with limited range or large range requirements, limited dispersal abilities, and species which are already suffering from habitat loss and fragmentation. In this chapter we use the case studies to identify the types of sensitivities for each species.

The effects of episodic, extreme events such as severe storms, floods and droughts are illustrated along the right side of Figure 5.1. The **degree, timing, duration** and **frequency** of such events can all reduce the **survival** and **fecundity** of plant and animal populations. Each parameter of extreme events can have different effects on the wildlife populations of the baylands; a brief and rare extreme event can have different impacts than a less extreme event that is frequent and prolonged. The impacts of events can interact; droughts in California have often been ended with a flood year – so a population that is reduced by drought must then cope with the impacts of flood. Increased frequency of extreme weather event will reduce the time available for a population to recover before the next extreme event occurs. Such events are expected to be both more frequent and more intense (Flick et al. 2003, Dettinger 2011, Cayan et al. 2012).

Episodic events test the resilience of wildlife populations. A single extreme event can have serious consequences for a local population (Zedler et al. 1989, Callaway and Zedler 2004). Extreme events may directly reduce the **survival** of members of the population; extreme events may reduce nesting success or feeding success thus reducing **fecundity**. Reductions in survival and fecundity will reduce the **recovery rate and ability** of the population. If the degree or frequency of catastrophic events exceeds the capacity of a population to recover then the population is at risk of extinction. If populations cannot reestablish themselves (following local extirpation) the species is at risk of extinction. Species at greatest risk will be species with low fecundity, limited dispersal effectiveness, and/or high mortality due to anthropogenic or other impacts. Species of already reduced population size because of ongoing or previous stressors are at enhanced risk.

The exact nature of episodic stressors must be defined with respect to the sensitivities of individual species. The temperature tolerances of one wildlife species will determine whether or not a particularly hot summer will decimate the population. Conversely, extensive and diverse habitats are likely to provide more thermal refugia for a given species and thereby reduce the impacts of extreme events. Long-term trends can also have important impacts on the long-term average abundance of a population that render them less resilient overall. Our conceptual model emphasizes that species are affected by both year-to-year variability in conditions as well as by long-term trends.

Table 5.1. Summary of case studies.

General Category	Species	Sub-category, i.e., what is it indicative of	Habitat	resident vs. migrant
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 inter-tidal	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	multi-habitat	resident, multi-habitat
Water Birds	American avocet, western sandpiper	avocet: large shorebirds; sandpiper: small shorebird;	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 included	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
Herps	California toad	wetland amphibian	wetlands	resident
	California red-legged frog	wetland amphibian	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	plants, crustaceans, other invertebrates, plants	multiple taxa	freshwater, ephemeral pools	resident
Plants: *Spartina*	invasive Spartina	invasive and native *Spartina*	tidal marsh	resident
Plants: rare and important plants	submersed aquatic vegetation	multiple species	open water	resident
	low tidal marsh graminoids	multiple species	tidal marsh	resident
	high tidal marsh annual forbs & 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 ecotone (transition zone)	resident
	terrestrial ecotone psammophyte	multiple species	terrestrial ecotone (transition zone)	resident

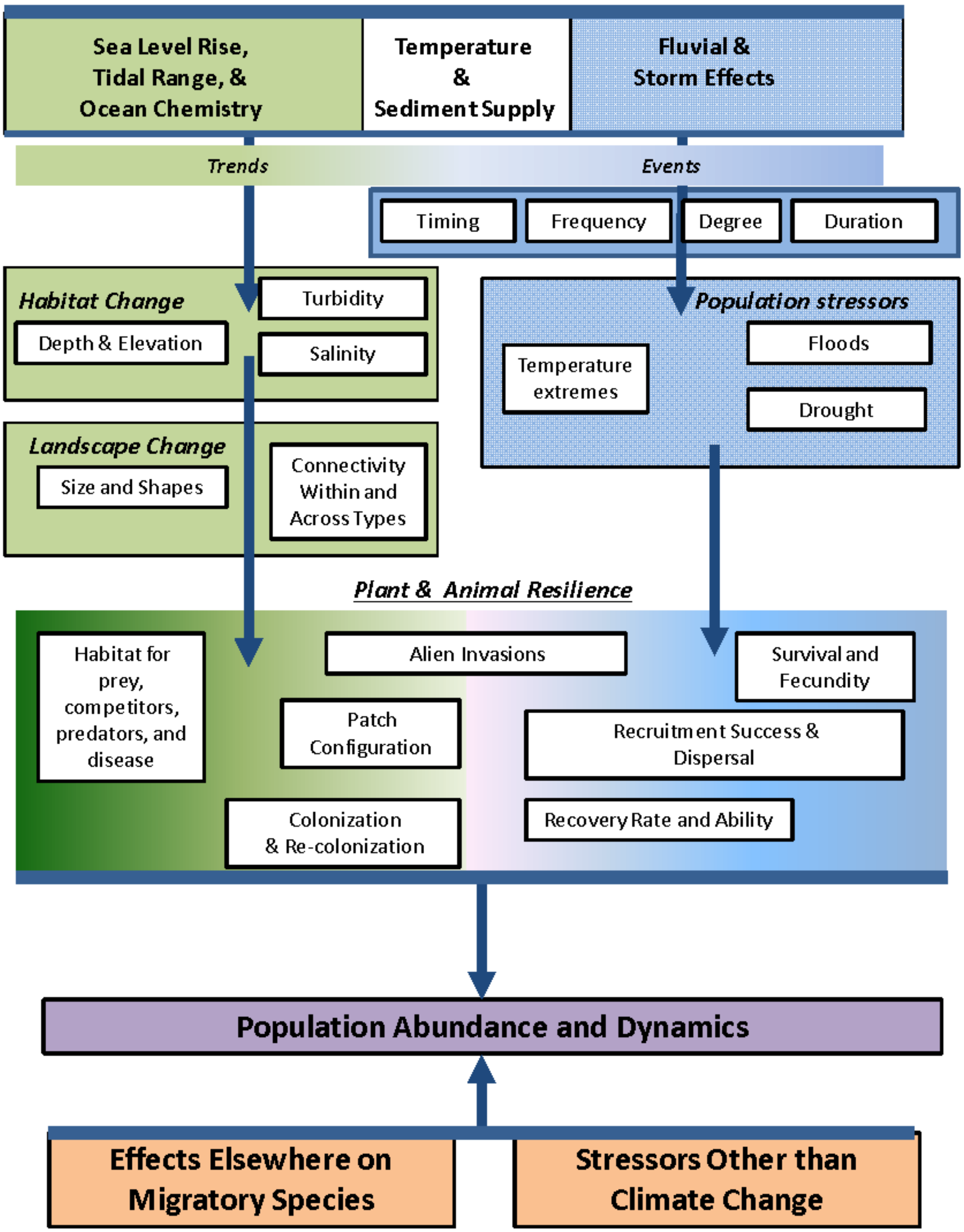

Figure 5.1. Conceptual model of climate change impacts on bayland wildlife. The left (green) side traces the impacts of long-term trends on the habitats and landscape occupied by wildlife. The right (blue) side traces the impact of episodic, extreme events and other factors that will affect population processes, and thus population size, trends, and resilience. Temperature affects both sides. Combined, these factors determine the abundance and dynamics of wildlife populations.

Combined Patterns

In the center of Figure 5.1 are three aspects of climate change impacts on wildlife that operate both as episodic, unpredictable events and long term trends: **temperature, sediment supply,** and **alien invasions**.

Climate change is expected to raise temperatures in California and thereby produce less snow in the mountains and more rain. Thus, even with no change in total precipitation, the timing, duration and degree of outflow will change on the short time scale, while on the longer time scale we expect increased frequency, degree and duration of droughts and floods (Science Foundation Chapter 1. Changes in air temperature in the estuary will have local effects on the reproduction and survival of many plants and animals; in many cases, changes in plant growth and reproduction will have secondary impacts on the animals that depend on them.

Sediment processes have significantly changed in the estuary as described in Science Foundation Chapter 1. Gold mining, water management, urban development and dredging have all affected the sources and supplies of sediments in the estuary. Future water development, habitat restoration, climate change, and catastrophic levee failure all have the potential to shift sediment dynamics in the estuary both gradually and suddenly. Impacts of such change are difficult to predict and are likely to vary in different parts of the estuary. We have relied on the projected habitat changes described elsewhere (Science Foundation Chapter 2 and its Appendix 2.1) and only here briefly summarize expected habitat change reflecting sedimentation. Invasion by alien species is an excellent example of an episodic event, often traceable to a single date or event for each successful invasion. However, long-term changes in habitat are often an important precursor to successful invasion. The responses of humans and wildlife to climate change may facilitate invasion by new species in the estuary. Such invasions will include new diseases, competitors, predators and prey, but may also release species that are currently present at low numbers to become new dominant species (as happened with *Egeria* and largemouth bass in the delta over the last 20 years; Santos et al. 2011).

Climate Change Impacts in Context

For all species the impacts of climate change constitute only one set of stressors they must deal with. Shifts in **stressors other than climate change** may exacerbate the impacts of climate change or affect the resilience of populations to respond to such impacts; both need to be considered.

For migratory species, conditions elsewhere (in the ocean, in the arctic, in Mexico, etc.) may override any efforts we make to protect them while they are present in the estuary. Conversely, changes in the ecology of migratory species elsewhere may make the baylands here more important than before.

The biology of bayland wildlife populations have been strongly affected by harvest, habitat change and California's exceptionally variable weather. Many of our aquatic and avian wildlife species are strongly affected by conditions outside the bay, either in the ocean or on summering and wintering grounds. Climate change will alter the impacts of both human impacts and weather and produce significant changes in the **population abundance and dynamics** of many valued species.

FUTURE CONDITIONS AFFECTING WILDLIFE

As part of the Bayland Ecosystems Habitat Goals Update project, five principal climate change scenarios have been delineated (Chapter I Science Summary). Here we consider the short-term and long-term impacts of such changes for wildlife.

Future Scenarios of Climate Change and Impacts for Wildlife

We summarize the five climate change scenarios considered in the Bayland Goals Update Project, which we refer to as Scenarios 1-5. Note that the first four scenarios considered combinations of either low sea-level rise (0.52 m over 100 years; Scenarios 1, 3) or high sea-level rise (1.65 m over 100 years; Scenarios 2, 4) and either low sediment concentration (Scenarios 1, 2) or high sediment concentration (Scenarios 3, 4). Each of these 4 scenarios in turn allowed for two sets of projections with regard to temperature, precipitation, snowmelt, runoff, and salinity: the **Ga** projection (much warmer and drier) and the **Pb** projection (moderately warmer, but no change in precipitation). Both sets of projections posit that future conditions will include:

- Warmer air
- Higher salinity
- Decline in snowmelt contribution to runoff, with a possible decline in precipitation and runoff
- Earlier runoff in winter and thus less water in late spring, summer
- Possibly lower suspended sediment concentrations (not likely to increase)

Of special concern for wildlife, the scenarios project:

- Increasing frequency of extreme environmental conditions such as higher water temperatures, higher storm surges, higher flood peaks, and possibly droughts

Predictions regarding future habitat extent and configuration differ strongly among Scenarios 1-4. To facilitate comparison, here we focus on the two most extreme of the first four scenarios: Scenario 2 (High sea-level rise, low sediment concentration) and Scenario 3 (Low sea-level rise, high sediment concentration); results for Scenarios 1 and 4 are intermediate with respect to 2 and 3.

The habitat projections of the four Scenarios are of particular concern with regard to tidal marsh habitat, which is divided into low marsh, mid-marsh, and high marsh, as well as tidal (or mud) flats. Different species depend on the three different tidal marsh sub-habitats (as described in the case studies and in this chapter). However, the total amount of tidal marsh habitat is also a fundamental concern, and so we summarize "combined marsh" as well, which includes all three marsh sub-habitats. We do so for three time periods: from 2010 to 2030; to 2050; and to 2110.

An important restriction on these projections is that they do not include **specific** restoration efforts which have been implemented since 2010 or will be in the future. Instead there are two projection modes: either (1) no restoration is assumed or (2) restoration in diked baylands occurs everywhere—that is, all levees are assumed to have been removed as of 2010, allowing restoration to occur. However, the actual time course of restoration is not modeled. Therefore in the following summaries we consider model output with regard to two extremes: no restoration and complete restoration everywhere. For change to 2030 and to 2050, we consider only "no restoration". That is, model output depicts what would be expected due to changes in elevation and salinity alone, without assuming specific restoration outcomes. For 2110, we present comparable results as well, but in addition we also summarize change in habitat if all levees were removed as of 2010 and assume that by 2110 restoration was complete.

<u>2010 to 2030 (No restoration):</u>

For Scenario 2 (**Hi SLR/low sediment):**

- increase in mid marsh (+26%) and low marsh (+14%); slight increase in mudflat (+2%). loss of high marsh (-54%).
- note that combined marsh increases 8%.

For Scenario 3 (**Lo SLR/high sediment)**:

- increase in mid marsh (+73%). loss of low marsh (-32%), high marsh (-32%) and mudflat (-46%).
- note that combined marsh increases +29%.

Thus, mid-marsh habitat increases and high-marsh habitat decreases under both scenarios, but projections regarding mudflats differ: either little change or substantial decline.

<u>to 2050 (No restoration):</u>

For Scenario 2 (**Hi SLR/low sediment):**

- increase in low marsh (+95% compared to 2010), decrease in mid-marsh, decrease in high marsh. For mid-marsh, though, the net loss is only -4%. By 2050 -75% net loss of high marsh (without considering any additional restoration). Mudflats continue to increase (+16% comparing 2050 to 2010).
- Combined marsh is +5.8% net increase for 2010 to 2050.

For Scenario 3 (**Lo SLR/high sediment)**:

- increase in low marsh (+4% net increase from 2010 to 2050, following decrease from 2010 to 2030), increase in mid-marsh (net increase of +101%), continued decrease of high marsh (net decrease of -54%). Mudflats also continue to decrease, strongly (-80% comparing 2050 to 2010).
- Combined marsh shows continued increase (+49% net increase).
  Thus, total marsh habitat increases (from 2010 to 2050) but high marsh decreases substantially under both scenarios. Projections regarding mid marsh and mudflat differ, depending on Scenario.

<u>to 2110 (No restoration):</u>

For Scenario 2 (**Hi SLR/low sediment):**

- Compared to 2010, very significant decrease in mid marsh and high marsh (-94% decrease or greater). Increase in low marsh (38% if we look only at current tidal, no additional restoration). Mudflat continues to increase (net +158%).
- There is 63% decrease for combined marsh compared to current tidal marsh.
  In short, low marsh increases, mudflats increase, others decline.

For Scenario 3 (**Lo SLR/high sediment)**:

- Low marsh shows strong decrease (from +4% increase by 2050 to net -65% decrease in 2110). Mid marsh continues to increase (net increase from 2010 to 2110: +158%). High marsh continues to decrease (net change, -80% comparing 2110 to 2010). Mudflats continue to decrease (net -91%).
- Combined marsh continues to increase to +61%.
  In short mid-marsh is a big winner; low and high marsh decrease, as do mudflats.

to 2110 (complete restoration):

For Scenario 2 (**Hi SLR/low sediment):**
If all levees are removed, resulting in full restoration by 2110, there would be a slight increase in combined marsh compared to the present tidal marsh (net +1.7%). Nevertheless, there would still be strong decrease in mid marsh and high marsh (-42%, -57% respectively). Mudflats are expected to increase (net +33%).

For Scenario 3 (**Lo SLR/high sediment)**:

If all levees are removed resulting in full restoration by 2110, there would be a large increase in combined marsh compared to the present tidal marsh (net +327%). There would be strong increases in low and mid marsh (+129%, +523% respectively) compared to the present. For high marsh, though, there would still be -26% decrease compared to present tidal high marsh. Mudflats are expected to decrease (net -64%).

In short, model projections indicate loss of high marsh under all Scenarios; the change in mid marsh and total marsh depends on the Scenario, but note that under Scenario 2, the net habitat change is more than 90% loss for mid and high marsh by 2110.

The above synopsis focuses on the total amount of habitat in the estuary. We must also consider sub-regional changes (see Science Foundation Chapter 2, Appendix 2.1) as well. Another important implication of these models is that habitat will change in a fundamental fashion from what it is now. Current wetland habitat, whether low, mid, or high marsh, or mudflat, will not as a rule remain as it is, at least not in the long-term. **Thus, the ability of organisms to successfully disperse to and colonize new habitat is essential.**

Scenario 5 concerns an extreme event: a hypothetical winter storm associated with flooding and extended inundation. The particular example modeled is that of a late January storm lasting for 2 weeks, but whose effects last even longer. Astronomical high tides at this time of year, El Niño, and the storm all contribute to extreme high water levels (Figure 5.2). Wind waves and changes in salinity can be expected. One of the most significant aspects of such a storm is extensive inundation of habitat, which may affect survival of tidal marsh wildlife (if there are no adequate refugia), and would likely reduce ability to forage for many animals (Thorne et al. 2013). While this scenario is hypothetical, Thorne et al. (2013) document two such severe and long-lasting events in San Francisco Bay tidal marshes: one in January 2010 and a second in March 2011. In the latter event, inundation nearly tripled compared to the non-storm period; such long periods of inundation will strongly affect many plant and wildlife species, as we discuss in this chapter.

The future of non-tidal, managed habitat

As important as intertidal habitat is, we must also be concerned with diked bayland habitat, which currently composes a substantial proportion of bayland habitat. These are low-lying areas around the Bay that were once tidal but now receive very little to no tidal action. There are several types of diked bayland habitat and some are especially valuable to wildlife. Of particular note are **managed ponds**, a category which includes both "salt ponds" (ponds that currently produce or in the past produced salt) and storage/treatment ponds. In this chapter we are particularly concerned with those managed ponds that, to a greater or lesser extent, are operated to maximize the value to wildlife. These are constructed habitats within the Bay, but at present managed ponds play a vital role for many wildlife species, such as shorebirds and waterfowl. Salinities of these non-tidal habitats are changing and will continue to change, especially as current managed ponds are converted to restored tidal marsh. Reductions in salinity of managed ponds will strongly impact prey availability for many waterbird species (Takekawa et al. 2009).

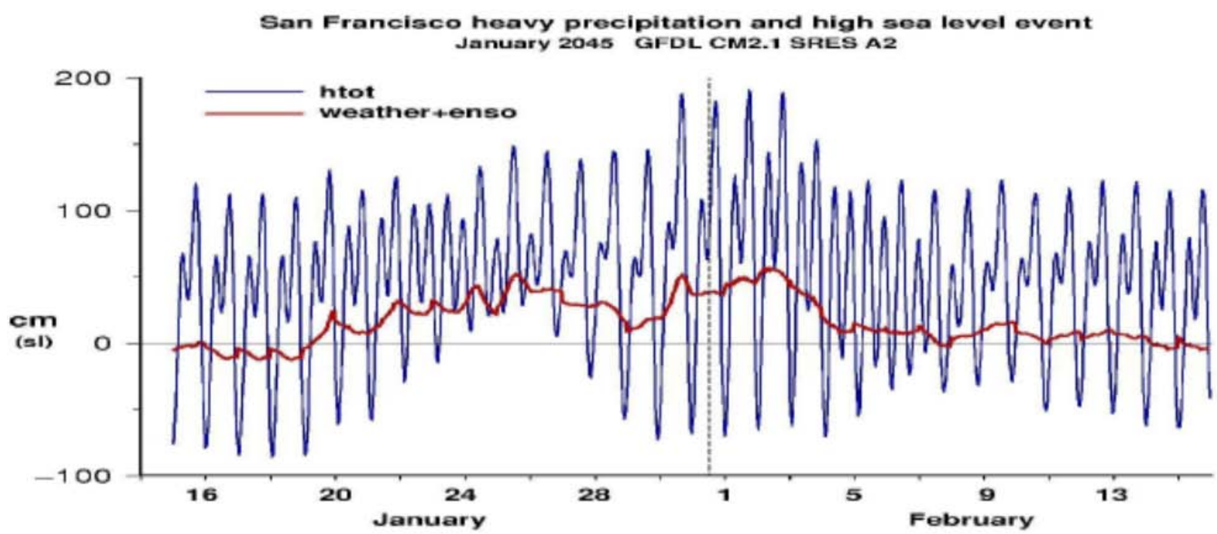

Figure 5.2. Scenario 5: Winter storm event. Scenario provided by D. Cayan (Scripps Institute). The Y-axis depicts fluctuation in water levels during the simulation (total water level in blue) with the portion due to the storm in conjunction with the ENSO event depicted in red.

Physical Effects on Wildlife and their Habitat

Science Foundation Chapters 1 and 2 describe climate change impacts on the physical characteristics of the bayland ecosystems; Science Foundation Chapter 3 describes physical and biological effects climate change will have from the ocean side. Here we attempt to identify some of the ways that climate change will affect bayland plants and animals. We consider broad patterns common to many species as well as more specific issues raised in the various case studies.

We consider four major categories of environmental drivers (see Figure 5.1, Conceptual Model):

1. Ocean Effects: Long term trends in salinity, nutrients and tidal heights

2. Weather effects: Short-term events including storm surges, freshwater flows, contaminants, and suspended sediments.

3. Geometry: Changes in bathymetry and the nature of the land:water interface.

4. Temperature: Changes in aquatic and aerial thermal regimes.

Ocean Effects

Salinity

Increasing salinity due to sea-level rise will directly affect most plants and aquatic animals, almost all of which have salinity as a principal determinant of their distributions. Fish communities of the estuary differ in species composition primarily due to different salinities in different areas. Strictly freshwater fish that currently can be found in Suisun Marsh will become rare. On the other hand strictly marine fish, including halibut, flounders and white seabass are likely to become more common components of the fish community of Central San Francisco Bay (Moyle et al. 2012). Amphibians require, at least at some life stage, freshwater conditions so they are likely to move upstream from some of their present locations. Plant distributions, persistence, and species composition will all be affected by changes in salinity and by the combined impact of salinity and inundation (see below; Parker et al. 2012b; Grewell et al. 2014). For plants, soil salinity is of particular importance, not simply the salinity of adjacent channels and the bay (Parker et al. 2012a).

Shorebirds and other waterbird species are strongly affected by changes in salinity, often acting through changes in their prey (Warnock et al. 2002, Takekawa et al. 2006b). Terrestrial birds and mammals are less directly affected by changes in salinity but changes in plant distribution are expected to strongly alter distributions of terrestrial vertebrates. Veloz et al. (2013) found that the projected change in salinity was the most important predictor of future population trends for tidal marsh birds in the San Francisco Estuary, presumably acting through projected changes in vegetation.

Water depth and inundation

Inundation of bayland habitat is projected to increase, due to both sea-level rise and to storm events (Cayan et al. 2012, Thorne et al. 2013, Nur et al. 2012). Long-term effects of sea-level rise on inundation patterns and water depths will be a function of geometry (see below) and substrate. Where inundation is not constrained by human infrastructure, the depth profile will move landward also. That is, erosion and sediment dispersion in newly inundated areas will reconstruct the typical gentle gradient of depths from marshes to sub-tidal areas. Where substrate or infrastructure will not allow erosion, habitats will be lost to excessive water depth as described in Science Foundation Chapter 1 (Knowles and Cayan 2002, Knowles 2010).

In areas with less adequate levees at present, particularly Suisun Marsh and the Delta, levee failure is almost inevitable and will result in inundation of many areas (Lund et al. 2007, Moyle 2008, Moyle et al. 2012, Moyle et al. 2014).

Dissipation of tidal energy into larger inundated areas near the mouths of the rivers draining the Central Valley will make the salinity gradient steeper and reduce the average area of suitable habitat for mesohaline species, like delta smelt. Such habitat alternation will be more pronounced in the mesohaline waters of San Pablo and Suisun bays, than the more oceanic waters of the Central Bay or the lagoon-like waters of South Bay.

<u>Other effects</u>
Increased intrusion of ocean waters will bring other features of ocean water into the bay, including cooler, more nutrient-rich waters under most climate-change scenarios, and increased acidification. These factors are likely to be much less important to wildlife than changes in salinity. There is little evidence of nutrient limitation in bayland ecosystems. Ocean acidification effects on bay water chemistry are unclear (see Science Foundation Chapter 3), but may limit the ability of larval invertebrates to accumulate enough calcium for shell growth.

Wildlife species that can move inland to follow the change in mean salinity distributions will be exposed to different physical conditions, potential isolation from other habitats, and new sorts of stressors. Species with less dispersal ability will be subjected to changes in the habitats they occupy. Later in this chapter we detail some of the likely negative effects on particular species.

Weather Effects
Decreasing snowfall in California is the most notable historic impact of climate change, and is likely to intensify (Roos 1989, Knowles and Cayan 2002). Increasing demand for a shrinking amount of available precipitation will likely yield more aggressive water management in the Central Valley. Together, these effects will produce shorter, sharper outflow events in the winter and longer seasons of low flow, beginning earlier in the spring and lasting longer through the fall (Stewart et al. 2005). Organisms of thermal sensitivity (like salmon), or which require a minimal duration of wetness (like the California red-legged frog) are at risk.

Storms are projected to be more frequent and likely more intense (Thorne et al. 2013). Pacific coast storms have increased in frequency and intensity in recent decades (Graham and Diaz 2001) and there is reason to be concerned about additional increases as a result of climate change. Peaks in streamflow and floods are predicted to occur earlier (Stevenson et al. 2005).

Storms are associated with high winds and stressful environmental conditions, which may lead to direct mortality or to increased mortality as a result of restrictions on foraging activity or reproductive success. Storms can have catastrophic effects on tidal wetland habitat (Zedler et al. 1989, Hilgartner and Brush 2006).

Intense storms following prolonged periods of dry conditions will intensify the loads of contaminants mobilized by the first flushing flows in each year, in particular mercury (Bergamaschi et al. 2001, Takekawa et al. 2006b). This will be true on a large scale due to flows from the vast urban and agricultural watershed of the Central Valley, but may be at least as important in each of the smaller watersheds draining into the bay. Management of stormwater runoff to protect wildlife, particularly aquatic wildlife, is likely to increase in importance.

Occasional tropical-weather based events (the 'atmospheric rivers' of Dettinger [2011]), are likely to become more common and produce rainfall events of large volume. Such extreme events, as in 1983 and 1997, have had significant impacts on diverse wildlife from plants to tidal marsh song sparrows (Zedler 2010, Point Blue Conservation Science, unpublished).

Sediment transport will be altered by changes in the pattern of water flow, as well as by changes in the sources of sediments to the estuary. Sediment loads have been decreasing for decades due to dam construction and the reduction in sediment loads from gold rush activities (Schoellhamer 2011). Particle sizes of sediments have gotten smaller as watershed development and dam operations preclude the movement of larger particles. Sediment loads are apt to decrease further as both intentional and catastrophic levee breaches produce new sediment traps. On the other hand, rising sea levels will expose new areas to erosion in bay area water sheds which may mobilize coarser substrates that are useful to valued wildlife like grunion and tidewater gobies.

Geometry

Changes in bathymetry will occur through changes in depths and shifts in sediments, as described in the chapters (Science Foundation Chapters 2 and 3). In some areas sea-level rise will lead to gradually increasing inundation. However, in Suisun Marsh and the Delta, sea-level rise and/or higher flood peaks are likely to cause levee failure, producing large and rapid alterations of the geometry of the baylands. This transformation of habitats, from managed wetlands to subtidal, will have immediate impacts on the resident species while removing intertidal habitats from the estuary in the long term. Inundation of deeply subsided islands will produce lasting changes in mean salinity as described above, but also significantly change the bathymetry and hydrodynamics of the upper estuary.

Changes in geometry will produce changes in the area, placement and quality of diverse wildlife habitats. Increased depth will most directly reduce the habitats of shorebirds and dabbling ducks, as well as other waterbirds (Galbraith et al. 2002, Takekawa et al. 2009; see below for further discussion of depth of managed ponds). The indirect effects of changes in the inundated area in the bay are likely to affect almost all wildlife populations.

Temperature (Aerial and Water)

Temperature of estuary waters and air are predicted to rise (Ackerly et al. 2012, Cayan et al. 2012). Coastal ocean temperatures are predicted to fall as a result of greater upwelling off the California coast (Snyder et al. 2003); more upwelling will also result in a stronger thermal gradient as one moves away from the coast. The severity and duration of extreme temperature events, such as heat spells, are expected to increase (Cayan et al. 2012).

Increasing air temperature in Northern California has already produced long-term declines in precipitation as snow in the Sierra Nevada mountains (Roos 1989). Thus, despite uncertainty regarding the quantity of precipitation in Northern California, there is little doubt that it will fall more as rain and will more quickly flow downstream. Increasing demand for an increasingly limited amount of available water for human use will lead to more upstream storage and diversion. Thus, freshwater storm inflows to the bay will often be earlier in the water year (Stevenson et al. 2005) and of shorter duration, but probably greater intensity (Dettinger 2011). Annual inflows to the bay are likely to become a smaller percentage of total precipitation, especially outside of the storm season.

Warmer temperatures on the land will tend to steepen the thermal gradients from the ocean in summer months, but, even in winter months, storms are expected to be more severe, more frequent and of longer duration (Thorne et al. 2013). Sea-level rise will amplify the effects of storm waves on water courses and bayland margins (Cayan et al. 2012).

Summary of Combined Physical Impacts on Wildlife

Estuaries are defined as enclosed areas where salt water from the ocean mixes with freshwater from the land. Wildlife populations in estuaries array themselves along salinity gradients, either because of their own salinity tolerances or due to the salinity tolerances of the species they rely upon. San Francisco Estuary faces a future with increasing salt water intrusion as sea-level rises and decreasing freshwater inflows as more precipitation comes as rain rather than snow. Thus, the waters that inundate baylands will become more saline and species that rely on low to medium salinity conditions will be stressed.

Estuarine ecosystems are strongly affected by tidal action that moves nutrients and organisms twice each day across different habitats. Tides expose sedentary plants and animals to strongly changing conditions each day, to which they are well adapted. Changes in the geometry of the bay, such as would follow levee failure in Suisun Bay or the Delta, will greatly reduce tidal action. More ocean intrusion, less freshwater flow, and greater inundated areas with reduced tidal action will cause most of the northern estuary to become more like the lagoon nature of South San Francisco Bay (Cloern et al. 1985). Species adapted to varying salinities and temperatures and inundation patterns will have less of an advantage over specialist species. Species that rely on water currents to assist their movements among habitats will have reduced ability to move from habitat to habitat or to colonize suitable habitats elsewhere. More stable salinities and consistently warmer waters may facilitate the invasion of more species or in some cases re-establishment of species not recently seen.

The future wildlife of San Francisco Baylands will reflect these interacting physical changes, the biological changes we describe below, and the effectiveness of management actions to protect wildlife.

IMPACTS TO WILDLIFE

Here we summarize impacts of climate change on wildlife populations, based on the 32 case studies (listed in Table 5.1). The individual case study findings are summarized in Table S1. We first provide a quick overview by considering the 32 case studies grouped into five major categories: Marsh resident species; managed wetland (including managed ponds) and tidal flat, migratory and resident; transition zone (upland interface); aquatic species, not resident or breeding in the Baylands; aquatic species resident or breeding in the Baylands. We then provide a more detailed accounting of how climate change will affect bayland species by considering specific demographic processes.

Summary of Habitat Type

Marsh Residents

Case studies include: low marsh plants, high marsh plants (saline and brackish; 3 case studies), invasive and native Spartina, marsh plain invertebrates, longjaw mudsucker, Ridgway's rail (formerly clapper rail), black rail, song sparrow, Suisun shrew and salt marsh wandering shrew, salt marsh harvest mouse, and northern harrier. Main climate-change concerns are: loss of habitat due to sea-level rise, inundation of habitat during winter extreme tides and storms and during the breeding season coupled with lack of refugia, elevated predation due to human-associated predators (e.g., crows and domestic/feral cats) as well as increased access to tidal marsh by predators. Future changes in salinity and inundation regime will affect plants important to wildlife as well as rare plants. Tidal marsh habitat is very fragmented and therefore connectivity of habitat is a major concern. Some species can take advantage of diked wetland habitat for refuge, foraging, etc., (e.g., shrew species and salt marsh harvest mouse) and this should be considered.

Wildlife in Managed Wetlands, Including Ponds, and Tidal Flat (Migratory and Resident)
Case studies include: dabbling ducks; diving ducks; American avocet and western sandpiper; least tern and Forster's tern. Whereas some species use tidal marsh habitat (e.g., dabbling ducks), managed wetlands (especially managed ponds) is generally a preferred habitat, and thus future habitat loss is a concern due to planned habitat restoration. Changes in salinity and water depth are also of great concern. Mud flats are projected to be lost due to sea-level rise. Reproductive success is sensitive to environmental conditions, including mercury contamination. Species can be affected by shifts in prey, which may occur with climate change, but which are hard to predict.

Transition-zone (Upland Interface) Species
Case studies include: Terrestrial ecotone plants (2 case studies); vernal pool species; California red-legged frog; California toad; and river otter. Availability of fresh or brackish water is key; saltwater intrusion is a major concern. Reproduction is very sensitive to environmental conditions (e.g., to changes temperature, salinity). Grazing by cattle is a concern for vernal pool plants and animals. Many species have limited dispersal. Habitat is very limited and is fragmented and often not connected. Upland refugia are important for these species as they are for marsh species and for many waterbirds, especially during storms and flood events.

Aquatic Wildlife Not Resident or Breeding in the Baylands
Case studies include: Dungeness crab, Pacific herring, delta smelt, longfin smelt, chinook salmon and steelhead. These species live predominantly in the water column and so move into Baylands when tides or floods inundate them. Many use baylands as nursery habitats for their young. Year to year variation in salinity distributions can control which species are in a particular geographic area in a given year. Thus, climate change impacts on salinity will have substantial effects on these species. Several of the species can be expected to be strongly affected by conditions away from the bay (i.e., oceanic condition). Some species are widespread and others of very limited distribution. Some species, particularly salmon and steelhead must migrate through the entire estuary on their way to the sea; in some cases their speed of movement will be determined by their physiological condition as they leave their native streams. Other species are subtidal residents that extend their range into Baylands, or can be expected to use Baylands as more of the Baylands become subtidal with sea-level rise.

Aquatic Wildlife Resident or Breeding in the Baylands
Case studies include: submerged aquatic vegetation, tidewater goby, grunion, and harbor seals. Aquatic species that rely on baylands for their breeding suffered badly through the middle of the last century before environmental protection began to reverse the degradation of aquatic habitats. Some of these were extirpated and have not yet returned but climate change and environmental clean-up is expected to facilitate their successful return or re-introduction. Habitat loss due to climate change may have substantial impacts if their breeding habitats are not ensured. Anticipated changes in salinity will have major impacts.

How Climate Change Will Affect Wildlife

Survival and Growth of Organisms
Tidal marsh birds and mammals are particularly susceptible to the effects of inundation and storm events. Thorne et al. (2013) report that, during a strong winter storm, foraging habitat for black rails at a tidal

marsh was unavailable for many hours over several days (Table 5.2). The presumed stress on this species was not just due to the extreme level of water experienced by terrestrial animals, but also due to the duration of inundation, during which time black rails could not adequately forage in the marsh.

Inundation of marsh habitat can lead to direct mortality for terrestrial organisms that are poor swimmers, such as salt marsh harvest mice. Of particular concern, even for mobile organisms such as birds, inundation leads to greater risk of predation. Marsh inundation may force individuals into the upland edge of the marsh (i.e., Transition Zone), or to cling to tall vegetation, where individuals are much more susceptible to predation (Evens and Page 1986, Shellhammer 2000). Thus, marsh inundation interacts with predation (see below, **Species Interactions**). This mortality pressure, due to the simultaneous effects of marsh inundation and predation, is expected to increase due to climate change (Takekawa et al. in press). This mortality pressure is well demonstrated in the Ridgway's rail. Overton et al. (2014) found that weekly survival of radio-marked Ridgway's rails was negatively correlated with the extreme tide for the week. An example of especially high tides in a tidal marsh is depicted in Figure 5.3. The researchers concluded that predation was the predominant cause of the increase in mortality, and such mortality has likely affected recent population trends for this species (Nur et al. 2012).

Table 5.2. Inundation of marsh habitat during winter and early-spring storms. Percent of vertical vegetative habitat inundated during a winter storm in 2010 and an early spring storm in 2011 (from Thorne et al. 2013). The March 2011 storm had 80 -90% of the available habitat inundated and therefore functionally unavailable for wildlife. March 2011 storm had over 90% of the vegetative habitat under water during the Max SLH at all sites. Mean higher high water (MHHW) and maximum sea level height (SLH) were determined from water level loggers deployed in 2nd order channels.

	January 2010		March 2011			
	MHHW Non-Storm	MHHW Storm	Max SLH Storm	MHHW Non-Storm	MHHW Storm	Max SLH Storm
Coon Island	40.88	55.95	65.41	7.46	80.94	93.59
Petaluma Marsh	46.58	73.90	78.52	15.55	92.85	97.78
San Pablo Bay NWR	54.27	65.46	72.23	23.45	90.00	95.85

With longer inundation periods, aquatic species of higher salinity marshes, such as longjaw mudsuckers and Dungeness crabs, may have reduced exposure to avian predators and increased foraging times. However, higher temperatures during the periods of exposure may override the benefits of increased inundation. Neither the available data nor current climate models are adequate to evaluate these trade-offs.
Extreme temperatures may result in direct mortality. Increased mortality of lizards has been linked to an increase in ambient temperature as a result of climate change, because it reduces the number of hours per day that lizards can forage (Sinervo et al. 2010, 2011). While those studies were of terrestrial species, the same considerations may apply to estuarine species: that is, increased temperatures may result in energetic imbalance for some species, leading to increased mortality. However, lower flows and higher salinities appear to be better for growth of salmon in baylands (MacFarlane 2010). Thus, climate change impacts may provide a benefit to salmon in the estuary. However, of much greater concern are the likely thermal stress and dewatering effects upstream, particularly on steelhead. Increased temperature and increased CO_2 levels due to climate change will affect plant growth and survival, affect recruitment and dispersal, change competitive advantages among plants (Parker et al. 2012b; Grewell et al. 2014) and will change ecosystem level processes such as decomposition, nutrient cycling, organic accretion and food web support (Grewell et al. 2014).

Figure 5.3. Tidal inundation of habitat used by tidal marsh birds and mammals, such as the California Ridgway's rail, reduces refuge availability and increases susceptibility of nests to flooding. (Photo courtesy C. Overton, USGS).

The frequency of hypersalinity events in salt marshes (i.e., drought years when channel water salinity and soil porewater salinity along marsh creek banks rises well above marine salinity) will likely be associated with years of mass gumplant dieback and reduced plant size (less cover, shorter gumplant canopy), as is currently the case and was the case in the early 1990s (and 1970s-80s). At the same time, high salinity may favor pickleweed (*Sarcocornia pacifica*) over the short term.

As inundation periods increase with sea level rise, the distribution and abundance of submerged aquatic plant species adapted to deeper flooding are expected to increase (Grewell et al. 2014). For many brackish plant species it is the combination of inundation and salinity that pose limitations when physiological tolerances are exceeded. Even plant species associated with salt marsh demonstrate high mortality when water levels and salinity are high (Parker et al. 2012a, 2012b; Woo and Takekawa 2012); the exception to this is *Spartina* (both native and non-native).

Shorebirds and diving ducks are energetically limited during the winter, as well as during their migration (Baldwin and Lovvorn 1994). Loss of mudflat habitat, which may result from sea-level rise exceeding rates of accretion of mudflats, could result in reduced survival of shorebirds (Crooks 2004, Galbraith et al. 2002, Galbraith et al. 2014). Furthermore, changes in water depth can affect accessibility of feeding areas for shorebirds. For diving ducks, they are more likely limited by the availability of prey species directly; climate-change induced change in prey species composition or abundance may lead to reduced survival.

Additionally, invasion or establishment of non-native species may lower survival as a result of competition, predation, or habitat change (see below).

Reproductive Success

Tidal marsh birds and other wetland-breeding birds (e.g., shorebirds) are susceptible to reproductive failure due to flooding of nests (Powell et al. 2002, Greenberg et al. 2006, Nur et al. 2012). Increased risk of nest-flooding reflects the combined effect of sea-level rise due to global warming, El Niño events, and storms, are all likely to increase due to climate change, as discussed above. Both the changes in mean high water levels and an increased risk of extreme events (storms, floods) are a concern. In the song sparrow, especially high water levels, whether due to extreme tides or storms, are strongly correlated with nest failure (Figure 5.4; Nur et al. 2012). Extreme water levels affect a nesting attempt that is underway. However, timing of extreme water levels is also important: the complete nesting cycle requires about 25 days. Whereas an extreme tide can cause failure of a nesting attempt that is underway, song sparrows will re-nest soon after the failure. However, if another extreme water event occurs within 25 days, then the re-nesting will also fail, which may lead to reproductive failure for an entire breeding season. A population model indicated that increased water levels, resulting from climate change, could, in the future, cause populations of tidal marsh song sparrows to decline by more than 80% over a 50-year period (Nur et al. 2012, Takekawa et al. in press). Black rails and Ridgway's rails exhibit the same sensitivity to nest failure as a result of extreme water levels. Nur et al. (2012) and Overton et al. (2014) inferred that nest failure due to flooding was a concern for Ridgway's rails (documented by Schwarzbach et al. 2006) and could reduce future population viability (Takekawa et al. in press). Small tidal marsh mammals (salt marsh harvest mice, bayland shrews) may also be at risk of reduced reproductive success or lower offspring survival due to flooding.

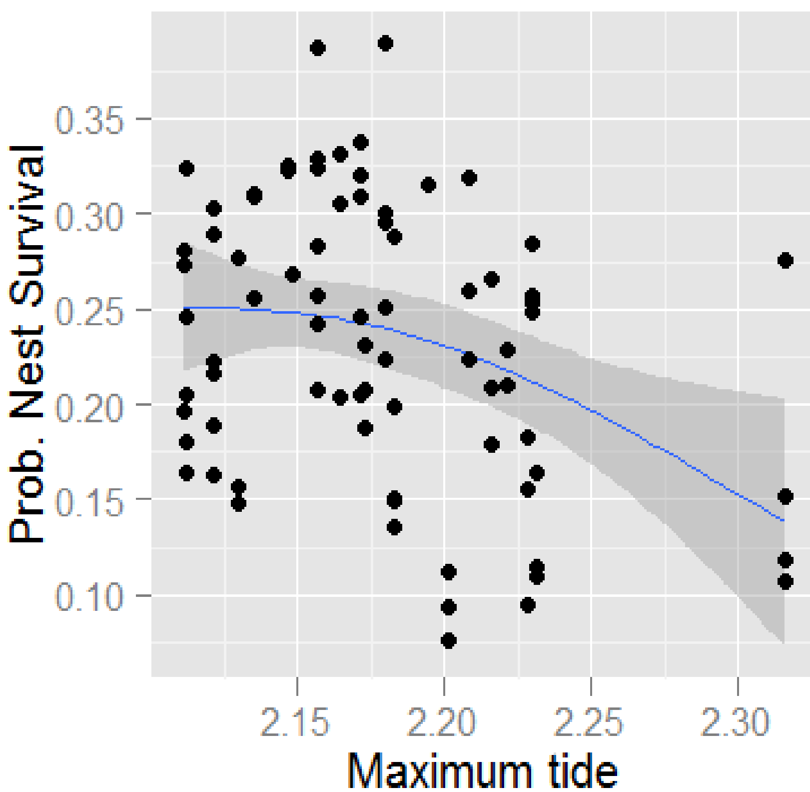

Figure 5.4. Song Sparrows: Nest survival and extreme tide. The greater the maximum tide experienced during the course of an entire breeding season, the lower is probability a nesting attempt survives to fledging (Nur et al. 2012). Extreme tides are expected to increase substantially in the future, especially over the next 30 to 100 years.

Amphibians, including the California toad and California red-legged frog, require freshwater ponds of sufficient depth and temperature. In particular, breeding ponds need to maintain appropriate conditions long enough for offspring to mature. Climate change may result in ponds drying out too fast or with excess salinity.

Many aquatic species have historically shown better survival or reproduction in years of higher outflow. The predicted restriction of outflow events to early in the water year is likely to restrict the spawning success of both longfin smelt and delta smelt. Particularly for delta smelt, the prolonged summertime conditions are likely to reduce survival and fecundity as the salinities they occupy in the summer and fall move upstream into less productive conditions of the delta. The broader distribution of longfin smelt may allow them to be less affected due to their ability to retreat to more oceanic waters. Pacific herring require a combination of solid substrates and appropriate salinity that is apt to become disconnected under the future climate. Suitable salinities will move upstream into San Pablo Bay, where the appropriate solid substrates are rarer, thus, eggs will be deposited on inappropriate substrates or in even greater densities on the limited patches of appropriate substrate. In either case egg survival is likely to decrease. Effects on the young, which use a wide variety of habitats, may be less severe.

Harbor seals require tidal flats of particular characteristics to haul out and birth pups (Figure 5.5). Loss of adequate haul outs (as a result of erosion or flooding of current tidal flats) 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.

Figure 5.5. Harbor seals depend on tidal flats to successfully rear pups. Sea-level rise will threaten current haul-out sites. Photo courtesy of S. Allen.

Many important plant species of the high-mid marsh are sensitive to salinity extremes. Many of these species may depend on a low-salinity period for germination during the winter and spring. This is of greatest concern for uncommon local endemic species, such as Suisun thistle and water hemlock (*Cicuta maculata*), which are patchily distributed, but applies to other plant species as well. For Suisun thistle, in addition to effects of salinity, inundation stress due to sea-level rise will also reduce the first order tidal channel habitat supporting Suisun thistle, and thus limit the distribution and abundance of populations throughout Suisun Marsh (Fiedler et al. 2014).

Species-Interactions

Predation

Predation is of high concern for animal species in bayland habitat (Greenberg et al. 2006, Nur et al. 2012). Tidal marsh-inhabitants are particularly susceptible, often subject to predators from adjoining uplands, including developed land adjacent to baylands (see Science Foundation Chapter 4). However, it is not clear that predation levels will, in general, increase due to climate change. In any case, current levels of predation are already straining the resilience of many bayland populations, leading to declining populations or ones that are not able to recover (Takekawa et al. 2012).

We suggest two pathways that may lead to increased predation on terrestrial species.

(1) Greater access by, and exposure to, non-native and human-associated predators. As a result of climate change, directly and indirectly, some predators (including those that are associated with or benefit from association with humans) may be more prevalent than at present or exposure to such predators may increase. Climate change may lead to "prey-switching," which can lead to heightened predation rates. Human population increase can contribute to this pathway for human-associated predators.

(2) Increased predation mortality specifically due to limited refugia, especially at times of stress or sensitive life stages; this is of concern especially regarding high water events.

These two factors interact, as shrinking wildlife habitats about human habitats and other sources of predation. Habitat is shrinking for species such as American avocets and snowy plovers not only due to climate change, but also due to extensive restoration activities impacting their current nesting habitat.

Management actions can affect one or the other of these two pathways, depending on the species and habitat under consideration. With regard to predator access, specific predictions are hard to make, other than that climate change will allow some predators to invade or establish themselves, which otherwise would not. Currently, California gulls are a species that has great predation impact on desirable bird species of bayland habitat (Shuford 2008). We are not able to predict whether climate change will increase predation rates, but that possibility is a concern, especially because habitat restriction (e.g., nesting habitat of snowy plovers) is increasing the susceptibility to predation.

Access of predators is often linked with human actions. Stocking of mosquitofish or sportfish into temporary ponds can have large impacts on reproduction of California red-legged frogs and California toads. Increased inundation and higher sea level is likely to produce mosquito problems in areas that at present are rarely wet enough. 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, and rats (Takekawa et al. 2006b).

High water events make tidal marsh birds and mammals especially vulnerable to predation. This is especially of concern for rail species and the salt marsh harvest mouse (Overton et al. 2014; Shellhammer 2000). River otters require dense vegetation refugia at times of high river flows. Designing habitats that function as refugia under extreme conditions will be an important part of planning for the impacts of climate change.

Disease

Risks due to disease are expected to increase (Harvell et al. 2002). Harvell et al. (2002) conclude: "[M]ost host-parasite systems are predicted to experience more frequent or severe disease impacts with warming" of the climate. In the temperate zone, shorter, milder winters are expected to increase disease spread (Harvell et al. 2002). Avian cholera, particularly on waterfowl, is currently a concern in the San Francisco Estuary (Takekawa et al. 2006b). However, projected climate change impacts for the incidence of the disease are not available. River otters are subject to disease, including emergent diseases; climate change resulting in reduced prey may affect susceptibility of otters to disease. Harbor seals may subject to pathogen shifts as a result of climate change, especially through increased proximity to terrestrial carriers of morbillivirus (dogs, cats, raccoons, skunks), *Leptospira* (rats), *Toxoplasma* (felines) and *Sarcocystis* (opossums) (Greig et al. 2014).

Amphibian chytridiomycosis (caused by *Batrachochytrium dendrobatis*) is of great concern for the California toad. Some warming may cause *B. dendrobatis* to spread or increase, but substantial increase in temperature may actually reduce the pathogen. As with many climate change impacts, this is of potential concern, but it is difficult to assess the risk due to climate change.

Incidence of plant diseases will likely be affected by many factors as a result of climate change (Garrett et al. 2006). Strong plant-microbial linkages, including that of mycorrhizal fungi, may help reduce disease (de Vries and Bardgett 2012); however, climate change predictions regarding microbes are difficult to obtain. For both plants and animals, there is concern that pathogens will evolve faster in response to climate change than host populations, and therefore spread more quickly with more virulent results (Garrett et al. 2006).

Community Composition

Species distribution models (Stralberg et al. 2009a, Ackerly et al. 2012) indicate that climate change will create new assemblages of species, thus changing the nature of competition among species. Climate change may cause non-native species to invade the baylands as well as species native to warmer parts of California to move into the San Francisco Estuary. Conversely current species may move out of the Estuary, as has been discussed above. Such changes in distribution could have direct and indirect effects. For example, a change in a predator could alter the balance among several competing species; a potential competitor may be "released" from limitations due to a reduction in predation. In general, the effects of these new assemblages on target species are not known, but there is potential for reduction in population viability. More studies are needed to identify the pathways by which a change in community composition affects target species. Because the risks are not yet identified, establishing a surveillance-monitoring program is recommended.

Interactions among aquatic species can often be affected more by changes in characteristics of water (salinity, temperature, dissolved oxygen, etc.) than by changes in the physical substrate that is the principal focus for terrestrial species. For example, re-establishment of oyster beds in San Francisco Bay is desired by many and may be an important tool in reducing the impacts of storm surge. Reduced sediment loads associated with future climate change impacts may facilitate the establishment of oyster beds. However, warmer temperatures and reduced circulation combine to produce lower dissolved oxygen levels that promote the spread of oyster drills that can decimate the population. As another example, the introduction of various Asian gobies that prey and compete with tidewater gobies may preclude the reestablishment of tidewater gobies into all of their former areas. Management actions that make such areas less suited for the invaders may be a necessary first step to re-establishing the native species.

Habitat Structure and Change

Plant Species Diversity and Structure

Species diversity is an important component of ecosystem resilience. Maintenance of plant species diversity, in particular, may be key: high plant diversity increases disease resistance (deVries and Bardgett 2012). Plant species diversity in a California tidal marsh was severely reduced by extreme events over the course of several decades, but the loss of diversity was particularly acute in 1984 due to the sequence of extreme events, in this case river mouth closure followed by drought (Zedler 2010).

Plants play an important role in providing suitable habitat, foraging locations, breeding sites and substrate, concealment from predators, etc., for many bayland animals. Vegetation structure is of particular importance for tidal marsh birds and mammals (Shellhammer 2000, Spautz et al. 2006). Gumplant (*Grindelia stricta*) plays an especially important role in tidal marsh because the uppermost part of this shrub can remain above high tides. However, gumplant is subject to die-backs, and thus mortality of this species (due to hydrology or salinity pressures) is a concern. Bulrush and tule play an important structural role in Suisun Marsh; increased salinity will cause important habitat change for tidal-marsh birds and mammals.

The important and complex role played by plants in structuring habitat and influencing wildlife species is well-illustrated by the non-native smooth cordgrass, *Spartina alterniflora* and its subsequent hybridization with the native Pacific cordgrass, *S. foliosa* (Guntenspergen and Nordby 2006, Grosholz et al. 2009). The hybrid *Spartina* has caused habitat changes at lower elevations in or adjacent to the marsh, leading to conversion of mudflats into vegetated, low marsh; at intertidal elevations native plants have been displaced by the invasive hybrid. Nevertheless, the invasive hybrid appears to have had a short-term beneficial impact on the Ridgway's rail. Lack of cover and refugia from high tides (during the winter and breeding season) have contributed to population declines of the Ridgway's rail prior to the invasion by *S. alterniflora*. In marshes which lacked adequate cover and/or refugia, the invasive Spartina provided needed vegetation cover.

However, there are numerous reasons to be concerned about changes in the habitat structure and characteristics as a result of establishment of the invasive *Spartina*, not the least of which is loss of critical mudflat habitat for shorebirds to forage in (Stralberg et al. 2004). Loss of the native *S. foliosa* is a second concern. The invertebrate assemblage of species is also altered as a result of the invasion (Grosholz et al. 2009). Finally, nest survival was reduced for tidal marsh song sparrows breeding in marshes which were invaded by hybrid Spartina (Nordby et al. 2009).

Habitat Connectivity

Compared to pre-human settlement conditions, bayland habitat is much more fragmented (SFEI EcoAtlas; Science Summary, this Report). Thus, connectivity among habitat patches has been reduced. Our emphasis in this chapter is on "functional connectivity," such that organisms, plants and animals, can move from one habitat patch to another, rather than contiguity of habitat. Even if connectivity is not further reduced in the future, the loss of connectivity, compared to pre-settlement, represents a serious risk to wildlife, because low connectivity reduces the resilience of wildlife populations.

Habitat connectivity is especially important in two regards: 1) For populations to be robust and resilient, successful dispersal is an important requirement. An isolated population is neither robust nor resilient: it is only a matter of time before it goes extinct. However subpopulations connected by dispersal are much more likely to persist. Habitat connectivity allows such a metapopulation to persist despite unpredictable and, in some cases, unfavorable conditions, for certain time periods or at specific locations (Hanski 1994). Migrant species also benefit from connectivity but their requirements will differ from that of year-round resident species. 2) Under several future scenarios, current bayland habitat (tidal flats, tidal marsh, etc.) is expected to change. What is currently high tidal marsh may become low marsh, low marsh may become tidal flats, tidal flats may become subtidal, etc. There may or may not be a net loss of habitat, but what we can expect is marsh (and other habitat) transgression, i.e., marshes will move, to the extent possible (Science Foundation Chapter 1). The implication is that habitat patches that are currently suitable will no longer be suitable, but that other areas within the landscape will become suitable habitat. As a result, if species (plant and animal) are to persist in the San Francisco Estuary, they will need to be able to move. And that will require connectivity of suitable habitat.

The ability to disperse successfully is an especially important limiting factor for many plant species. High tidal marsh annual forbs 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 non-native species (Grewell et al. 2013). As with other non-native invasive species, there are a number of annuals that are strong colonizers. Thus for the native marsh species of concern, active translocation may be required. A similar situation exists for plant species of vernal pools.

BACKGROUND TO RECCOMENDED ACTIONS

Strategy for Resilience

Several themes emerge from synthesizing the 32 case studies regarding impacts of climate change and how these can be addressed. These case studies and recommendations are based on the monitoring and special studies of wildlife in the estuary, despite the data gaps we describe. Climate change will cause habitats to shift, species to move, and communities to reorganize; our current monitoring programs will have to adapt if they are to provide the information that future management and protection will depend on. Developing a modeling framework for our changing estuary will require substantial effort and is essential to the management recommendations.

(1) Ensure Suitable Habitat in the Future

Habitat for bayland species will be difficult to protect because of the uncertainty associated with future projections (Stralberg et al. 2011, Veloz et al. 2013; Science Foundation Chapter 2). The uncertainty of climate projections and sea-level rise are of global concern and intensive predictive efforts are underway. For baylands in the San Francisco Estuary there is also considerable uncertainty about future suspended sediment loads and distributions, as described in Science Foundation Chapter 1. Two of the habitats of great concern for wildlife are tidal marsh habitat (both saline and brackish) and tidal flats. The range of possible amounts and distribution of tidal marsh has been modeled by many, but less so for tidal flats. However, tidal flats are a key resource for many wildlife species, such as shorebirds (for foraging) and harbor seals (for hauling out to rest and nurse their pups). In addition, estuarine beaches are an important habitat type for some plants (as described in the case study), shorebirds, and potentially grunion.

Concern about climate change is likely to lead to armoring levees, e.g., creating higher, more substantial seawalls. Armoring may protect humans and human infrastructure but will largely eliminate shallow habitats on the bayward side of the levee. As a result, important habitats, especially tidal marsh, tidal flats, and estuarine beaches will likely be reduced. An alternative to this armoring to protect humans and human infrastructure is for marshes, mudflats, beaches and oyster beds to play an important role in dissipating tidal energy from the levee and redirecting that energy onto nearby, less armored parts of the bay margin. In this paradigm, natural habitats provide not only ecosystem services to wildlife and plants by creation and protection of habitat, but also provide protection of levees and seawalls that are placed upslope of these natural habitats.

Some habitat types depend entirely on substantial human intervention: managed wetlands including commercial or former salt ponds, diked marshes, and muted tidal marshes. These habitat types, though dependent on continual management input, have a role to play with regard to the future habitat mosaic of the San Francisco Estuary; emphasis cannot remain solely with "self-maintaining habitat," to use the Goals Project (1999) label. Of particularly value for wildlife are **managed ponds**, a category that includes several types of ponds (salt ponds, storage/treatment ponds, etc.) that are managed to support wildlife. While no species in the San Francisco Bay region is a managed pond obligate, the loss and degradation of natural habitat for waterbirds in the past century has led to strong reliance on managed ponds at present. The Goals Project in 1999 set acreage goals for managed ponds, which entailed substantial recommended reduction in the amount of managed pond habitat, coupled with management directed at maintaining conditions (with regard to salinity and depth) that will support high densities of shorebirds, waterfowl, and other waterbirds, despite reduced acreage. Since publication of the Goals Report in 1999, we have acquired much specific information that will be invaluable in managing this habitat so as to maintain or increase abundance of shorebirds and waterfowl (Warnock et al. 2002; Takekawa et al. 2006a, Takekawa et al. 2009 ; Brand et al. 2014); see Theme #2, below (**Provide necessary habitat features**).

We highlight the importance of providing sufficient habitat specifically with regard to managed ponds for two reasons. Climate change will lead to increased water levels and changes in salinity (Science Foundation Chapters 2, 3 and 4) putting additional stresses on the network of levees and water control structures necessary for maintaining optimal managed pond conditions. Second, restoration of tidal marsh through the conversion of managed ponds has resulted and will result in less acreage available. Thus, there will be important challenges in future years to maintaining managed ponds so as to reduce adverse impacts on waterbird populations using this habitat. For example, investment in new water control structures may be required (Science Foundation Chapter 2). Increased reliance on pumping may also be necessary. However, design and management of these ponds should not be pursued in isolation: natural habitat, including tidal marsh and tidal flats provides important resources as well. In any case, it is clear that future environmental conditions such as higher water surface elevations, frequency and intensity of storm events, and regional salinity shifts will make it difficult to maintain target habitat conditions inside the ponds. For some current managed ponds, it will be difficult to retain those ponds as such and thus relocation (taking into account sea-level rise and future hydrological conditions) may be necessary. Thus, investment must consider both the long-term future of managed ponds as well as the future restoration of tidal wetlands containing ponded areas and other features that benefit the suite of species currently relying on managed ponds.

Diked marshes represent another important habitat; they can provide important resources for species usually associated with fully tidal marshland, such as salt marsh harvest mice and the two bayland shrew species. Case study authors recommend that diked marshes be included in the future mix for these species. Tidal marsh birds (such as song sparrows) may also benefit from muted tidal marshes; their value should be explored.

(2) Provide necessary habitat features, locally and across the landscape

Characteristics of a given habitat, at the local and landscape scales, are as important as habitat quantity. One important habitat feature is the width and extent of the marsh/terrestrial transition zone, which is treated in detail in Science Foundation Chapter 4. Salt marsh harvest mice and bayland shrews need a broad, gently-sloped natural transition zone with substantial vegetation; such a zone likely benefits black rails as well as other tidal marsh birds (Evens and Page 1986). Several plant species benefit from such transition zones. The transition zone has been degraded or lost (Science Foundation Chapter 4); this zone is narrower than in the past, and now abuts artificial levees and urbanized, or otherwise developed, lands. Restoration or re-creation of natural transition zones (as well as the bayland and terrestrial habitats on either side of them) will help many wildlife species. The need is acute especially as new levees are built to protect human infrastructure from climate change impacts. It is equally important to focus on the nature of the terrestrial habitat that borders the marsh habitat: predators and invasive species often enter the transition zone on the terrestrial side. Upland areas that will allow marsh transgression and transition zone values are likely to become rare, so all opportunities should be considered.

Refuge habitat from predation and extreme water levels (e.g., during especially high tides) is already of high importance and will become more important to wildlife populations in the face of climate change. Refugia may also be needed with respect to drought, which not only leads to drying up of pools and ponds, but also can lead to hypersalinity. Drought, hypersalinity, and extreme water levels are all likely climate change impacts; predation rates may also be affected. In particular, climate change may provide avenues for invasion by non-native or "nearby-native" species to move in. Human-associated predators (e.g., crows and ravens, gulls) already pose substantial risks which need to be addressed or in the future these risks may increase.

Ancient tidal marshes are characterized by a highly dendritic, sinuous network of tidal channels (Goals Project 1999). Tidal marsh-dependent plants and animals benefit from such channels. Thus, restoration efforts should give this habitat feature precedence. In this way, a restored marsh may be more valuable to wildlife than a 150-year old marsh created during the gold-rush period. In the face of climate change, marshes and adjacent habitat can be designed and placed to provide more resilience to wildlife than current older, or even ancient marshes do.

Design considerations can allow smaller areas to do more for their dependent populations.

For example, topographic relief in a marsh is of value; enhancing that topographic complexity through creation of marsh mounds and berms can enhance marsh heterogeneity, increase plant species diversity, and provide some barriers to water flow or refuge from highwater events.

Another example is to build gently-sloped transition zones, fed by brackish flow (the "horizontal levee"; TBI 2013). Freshwater ponds (for amphibians), vernal pools, and saline ponds can all be maintained with salinity and water levels subject to control to benefit wildlife.

Salinity is an important habitat characteristic for many species as discussed in this chapter. In particular, salinities have generally been lowered in managed ponds both in the North Bay and South Bay, as part of a long-term management strategy to ultimately convert managed former salt ponds into tidal marsh habitat (Stralberg et al. 2006), with fewer ponds exhibiting extreme salinity. The result has been a substantial increase in diving and dabbling ducks (Pitkin and Wood 2011). But such change has not necessarily been as favorable for shorebirds, some of which, such as the western sandpiper and American avocet, rely on the high densities of invertebrates (e.g., brine flies) found in hypersaline ponds (Brand et al. 2014). At the same time reduction in depth of water in managed ponds increases accessibility of foraging habitat for shorebirds (Warnock et al. 2002, Brand et al. 2014). Recent reduction in depth in some managed ponds has led to observed increases in shorebird numbers (Pitkin and Wood 2011). Thus, maintaining the optimal balance of salinity and water-depth in managed habitat will be important in the near future and for some time to come.

Management of salinity and water depth is an example of a recent trend, which will continue and accelerate in the future, to emphasize (from a management perspective) on quality of habitat, both with regard to features within a marsh or pond and also with regard to configuration of habitat. In this way, for example, a reduction in acreage of managed ponds can still potentially result in increases in abundance of shorebirds and diving ducks (Pitkin and Wood 2011), provided there is the ability to provide the specifics of salinity and water depth that benefit a range of waterbird species. Wildlife will require comprehensive planning efforts, such as a scenario planning effort for the South Bay Salt Pond Restoration Project which has recently been completed.

(3) Maintain or augment population resilience by addressing other stressors

A resilient population is better able to tolerate the effects of climate change, especially stresses due to extreme events such as droughts and floods. Such climate change impacts are difficult to address directly, but further reduction of known stressors will add to a population's ability to withstand new stressors (and is addressed in Chapter 2 of the main report – New Opportunities: How We Can Achieve Healthy, Resilent Baylands). A resilient population has sufficient reproductive success and survival to offset mortality, including occasional "catastrophic" mortality. Hence, knowledge of reproductive and survival rates is extremely desirable, though difficult to measure in the field. As a result, the monitoring of trends in abundance provides an initial and cost- effective means to assess if a species is in trouble. Where abundance has declined over time, research and management need to respond quickly to reverse that trend. Low nest survival of tidal marsh song sparrows has been implicated in their recent declines throughout the San Francisco Estuary (Nur et al. 2012). Ridgway's rails have demonstrated an increase in number relative to the 1990's, but a decrease from 2007 to 2013, with low first-year and adult survival the prime contributor (Overton et al. 2014). Such studies provide indication of where management should focus on to augment resilience.

Stable abundances or short-term positive trends provide no guarantee of the long-term health of a population. Therefore, a prudent approach is to address mortality sources for all target species, whether or not they are declining.

The following are stressors whose impacts could be reduced, independent of climate change, thus increasing population health and supporting resilience. Specific actions are discussed in Chapter 2 of the main report – New Opportunities: How We Can Achieve Healthy, Resilent Baylands

- **Predation, affecting both survival and reproductive success.** Section III summarizes these effects.

- **Contaminants.** Mercury contamination is of particular concern to birds and mammals. Pyrethroids are a major concern for aquatic species. "Emerging" contaminants (SFEI 2013 [RMP]) have been implicated in reducing the survival and reproductive success of many species. There are many other contaminants of concern.

- **Nuisance and invasive species; disturbance.** Management that targets nuisance and invasive species is often less controversial than other actions. Disturbance by humans (e.g., due to recreational use; dogs and their owners) can be reduced. Shorebirds and waterfowl benefit from reduced disturbance, as do harbor seals. If grunion return to the estuary it will be important to protect their spawned eggs from off-road vehicles.

- **Disease susceptibility.** Susceptibility can be reduced through improvement of physical condition, which in some cases reflects prey availability. Harbor seals, frogs and toads, and colonial (flocking) waterbirds are example of species subject to disease.

(4) Maintain resilience by increasing recruitment and dispersal success and facilitating movement at the local scale

Successful recruitment of offspring into the adult population is a necessary requirement for viable populations, and is even more important to produce populations robust to climate change and other stressors. The fragmented nature of current baylands places a strain on species' variability. The current patch of habitat occupied by a breeding animal or plant may be appropriate, but what is nearby may be inappropriate habitat or of poor quality. And yet, dispersal ability is limited for many bayland species of concern. Longjaw mudsucker, tidewater goby, vernal pool plants and invertebrates, salt marsh harvest mouse, and the bayland shrews appear to have limited dispersal abilities (Table 2). Rail species (black rail and Ridgway's rail) demonstrate low dispersal rates even when such movement would be adaptive (Overton et al. unpublished). Evolution of high site fidelity, and therefore low dispersal ability by these species, may have been adaptive in the past. In the current, fragmented landscape it is a problem. Changing landscapes due to climate change will surely worsen conditions for less dispersive species (see theme #5, below, **Manage for uncertainty**).

Restoration designs can address the problem of fragmentation by targeting functional connections (i.e., allowing effective movement and dispersal). Highways, levees, and other structures can be important impediments to successful dispersal; steps must be taken to address these barriers.

Species that live along water courses or the bay margin are better able to disperse because their habitats are physically linked and they exhibit good dispersal abilities. Such species include river otter, salmon, shorebirds, and harbor seals. Often these species can move within a water course or along the bay margin as conditions in one area change and they disperse easily to new areas because their habitats are connected by water. For these species, it is important to ensure that there are no barriers to successful movements among suitable habitats and that all habitats are within the dispersal distance of a healthy source population. Such barriers would include dams or channelized sections of streams or long unbroken stretches of levees on the bay margin.

Small population sizes increase population vulnerability. Small populations are more prone to local extinction, due to unpredictable mortality events and reduced fecundity reproduction when density is low (the "Allee" effect). Ridgway's rails may already demonstrate this phenomenon. The dangers of small population size are accentuated when sub-populations are isolated from each other. Small populations may require translocation from other locations or other active management to boost population size.

(5) Maintain resilience by managing for dynamic landscapes

The landscape of the San Francisco Estuary will change. The nature of that change is not well-established, though we expect that the velocity of climate change, and therefore its impacts, will be high in the human-altered landscape (Loarie et al. 2008, Ackerly et al. 2012). Not only will there be somewhat predictable change (sea-level rise will accelerate, temperatures will increase, including duration and frequency of heat spells, etc.), there will also be change of an unpredictable nature. Thus, as discussed above, wildlife populations will be subjected to more frequent, more extreme, and more unusual, stresses from California's changed climate. More habitat (see #1, above), possessing the appropriate characteristics (see #2, above) and allowing for dispersal and movement among suitable habitat patches (whether currently occupied or not; see #4, above) will all help species cope with climate change. But the changing and unpredictable nature of future landscapes will require even greater effort, monitoring, and specific planning. Thus, restoration design needs to go beyond simply improving on the present (more, better quality, better connected habitat). Therefore one recommendation (see Chapter 2 of the main report – New Opportunities: How We Can Achieve Healthy, Resilent Baylands) is to anticipate where mudflats or tidal marsh may migrate in the future, and design restoration or habitat enhancement accordingly.

To persist, plants and animals will need to move into suitable new habitats (Grewell et al. 2013). Such movement is required because once-suitable habitat will become unsuitable and vice versa. We anticipate that local occupied patches may be extirpated, or reduced to very low levels, due to the combination of extreme events and other stressors (disturbance, contaminants, non-native species, etc.). Protection of wildlife species will require designing landscapes with dispersal needs in mind. For some species of limited dispersal ability, or for which current barriers are too high, active translocation of individuals will be required, as currently occupied habitats are lost or degraded and new habitat is produced in other areas.

An additional protection against extinction is maintaining **genetic diversity**. The currently diverse and patchy landscape requires genetic diversity, and with future (unpredictable) change, genetic diversity is even more important. Many species of concern in the Baylands are composed of genetically distinct populations, and in some cases distinct subspecies; such differentiated species/subspecies include song sparrow, California red-legged frog, salt marsh harvest mouse, bayland shrews, black rail, and salmon. These species or subspecies represent valuable genetic diversity and adaptation to local conditions as evolutionary significant units (ESUs; Fraser & Bernatchez 2001). Often, however, these populations are small and so require high within-population genetic variation to maintain viability (Soulé 1986). We need to manage these genetically differentiated species to maintain their resilience and facilitate the re-colonization of suitable habitat following catastrophes. Re-colonization 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 for these species may be important in preserving the genetic diversity currently present so that bayland populations can respond to changed conditions on different time scales of climate change.

Isolated populations such as those of rare marsh plants and invertebrates of vernal pools represent unique products of evolution. However, these isolated populations have very little cross-breeding, and thus loss of a population due to catastrophe may represent a complete loss of some genetic diversity and must be avoided.

(6) Manage for uncertainty, including for extreme events and for the "unforeseen"

Uncertainty is used to describe two very different concepts:

1. Our lack of knowledge or precision about the physical parameters of the environment and the biology of the various species.

2. Unpredictable events that we know will happen but we don't know when, how much, etc. We can expect to be subject to unprecedented events, but cannot predict the specifics.
   Both kinds of uncertainty must be accommodated in developing management actions.

Difficulty in making predictions regarding climate change is discussed in Science Foundation Chapter 2. Changes in geomorphology and hydrology are also difficult to predict. Sedimentation rates are important parameters for many baylands that are likely to change, especially in light of future restoration projects and upstream water management. Future decisions regarding the maintenance or construction of infrastructure (e.g., levees) will affect future habitat. The result of all these influences is substantial uncertainty regarding future habitat extent and distribution. This source of uncertainty must be addressed in planning (Veloz et al. 2013).

However, in some cases, it is only the rate of change that is unknown. We know what will happen, but not when. Therefore one approach is to develop triggers for management action; when thresholds are crossed, management action is triggered. As described in the marsh plant case studies, examples of thresholds to be concerned with are:

- Recurrent failure of levees; overtopping or breaching of levees.
- Significant reconstruction or armoring of levees or new hydraulics.
- Low marsh vegetation dominates mid- to high-marsh in the marsh plain, where it wasn't before.
- Large-scale conversion of brackish marsh to saline marsh.

An additional component of uncertainty is the widespread lack of basic information for many species of concern. This is the case not only for rare species such as the bayland shrews, but for quite common species like river otters. River otters are becoming much more common in baylands, but we are ignorant as to whether that is the sign of a burgeoning population or of movement downstream from more disturbed areas upstream. In the case studies, important knowledge gaps for managing the species are described. The state-of-the-knowledge is particularly poor when it comes to what we need to know to manage for climate change. For many species, we don't know if populations currently are stable, declining, or increasing. For species that breed elsewhere, even if we have current trends for San Francisco Estuary, important information may be missing. For example, trends in wintering waterfowl (surf scoters and scaup) may reflect causal influences acting on their breeding grounds.

The approach needed to develop and respond to uncertainty is **adaptive management**, and that approach is particularly needed when it comes to climate change. We recommend the development and application of **population models that can incorporate environmental variability**. Such models can:

- consider different future scenarios,
- identify important bottlenecks and thresholds for species of interest, and
- incorporate environmental variability especially of the stochastic kind, i.e., the unpredictable extreme events.
- Such models can evaluate sensitivity of output to uncertainty of both kinds: lack of knowledge and unpredictability.

Additional monitoring and research studies must target important data gaps, evaluate model assumptions, and validate models. The models can be used to evaluate resilience and explore how resilience can be increased. The long-term response of wildlife populations to extreme events can be modeled. Monitoring could be conducted immediately after an extreme event to determine the population consequences of the event. Further monitoring can evaluate the recovery of the population, and this can be compared to model predictions. Information on turn-over (extirpation and re-colonization) of sites, including newly available sites as a result of restoration or habitat change, is needed to construct models that project how populations will grow, shrink, spread, or disappear across the entire bayland landscape. As we may need a stockpile of sandbags to deal with a broken levee, we need a toolbox for wildlife management to address the expected heat waves, floods, droughts, storm surges, winds, etc.

Important Data Gaps and Evaluation of Uncertainty

Here we summarize information on sources of uncertainty and important data gaps. Galbraith et al. (2014) provide a good outline of information needs for determining shorebird response to climate change and their work provides a good model for other species or groups. Uncertainty in climate change drivers is discussed in Science Foundation Chapter 1 and also in the section above ("Managing for uncertainty").

1. Information on population trends.

As previously noted, for many plant and animal species, we do not know if bayland populations at present are stable, declining, or increasing. This lack of information makes it difficult to develop appropriate management actions, as well as to prioritize those actions. Thus, an emphasis of trend monitoring, at the appropriate spatial scale is needed (see Section above).

One species of widespread conservation interest for which there is little information is the river otter *Luntra canadensis*. Otter are being seen more frequently and are reported from all bay area counties, including San Francisco. This may represent either a burgeoning population or a species losing all of its suitable habitat upstream. As an apex predator, the otter has significant ecological impacts on its prey species and may be a sentinel species for a variety of stressors that multiply through the food web. But at present little of its status or needs or impacts are understood.

For many bayland mammals, herps, invertebrates, and plants, we know little about their population trends. In contrast, for fish, population trends are known, at least in the open bay, as a result of surveys by the California Department of Fish and Wildlife (SEIT 2011), though not necessarily in bayland habitat. In addition, some individual fish species have been well-studied.

Population trends for many bird species in the San Francisco Estuary are known (Pitkin and Wood 2011). However, a number of bird species in the estuary breed elsewhere; for example, diving ducks are mainly present during the winter period. Use of the San Francisco Estuary is very important to the ducks, but winter-time trends in population are hard to interpret. Do the trends reflect population dynamics on the breeding grounds, or do they reflect shifts in their distribution? A shift may simply reflect increased or decreased suitability elsewhere rather than reflecting conditions or management action in the San Francisco Estuary. A similar problem exists for trends of western sandpiper and other shorebird species.

2. Information on underlying vital rates: survival, reproductive success, recruitment rates.

For many species for which population trend estimation is possible, we have little or no information on adult survival, reproductive success, juvenile survival, or recruitment success. In some cases, we may have information on just one of these rates; for example, reproductive success for tidal marsh song sparrows and least terns in San Francisco Estuary has been studied for a number of years as is the case for several dabbling duck species in Suisun Marsh. In the case of Ridgway's rails, there is some information on juvenile and adult survival, but very little current information on reproductive success. For California red-legged frogs, information on adult survival is lacking, but studies indicate that egg survival and larval survival are very low, pointing to these two parameters as key with respect to population viability and resilience and thus important targets for management action. Thus, information on even one demographic parameter is extremely valuable.

3. Causal influences on variation in demographic parameters.

In addition to estimation of demographic parameters, e.g., obtaining mean values, it is also essential to characterize variation (across space and time) in demographic rates, especially in relation to environmental variables. If we can understand how current populations respond to environmental variation, we will be better able to project how wildlife will respond to climate change and other stressors. In short, lack of information on demographic rates and how they are influenced by the environment represents a key uncertainty and a data gap that needs to be addressed.

The nature of variation in demographic rates is poorly known: How plastic are these rates? How do they respond to environmental variation, and over what spatial scale? One of the most important questions is, To what extent do these rates respond to management action? Empirical studies of birds indicate that a small difference in adult survival rates has a large effect on population trend. However, often reproductive success is much more responsive to management actions than is adult survival in many cases. Such information is crucial to projecting impacts of climate change on population health of wildlife and developing management actions to address these impacts (Nur et al. 2012).

How will changes in the habitat due to invasion by non-natives (e.g., hybrid *Spartina*) affect survival and reproductive success, both in the short-term (which may be feasible to study) and in the long-term (which, by its nature, is much more difficult to assess)?

4. **Information on population-level consequences of climate change**.

Many studies indicate that climate change may lead or has already led to a shift in timing of breeding or migration. In that case, what are the consequences of a change in timing for a species and for species that interact with that species? When and how do the species that make up a community change? What are the consequences of such changes on species of concern? A change in prey species may be different than a change in competitor species or a change in a predator.

5. **Information on dispersal success and the impact of management actions**.

For example, what are the important characteristics of dispersal corridors? What are critical time periods for dispersal? What are the characteristics of movement itself (during which organisms may be at risk of mortality)? What determines success with respect to recruitment in new or unoccupied areas? That is, information on behavior (to disperse or not, where to disperse) is needed as well as success at recruiting into the breeding population.

This information will be needed in order to make decisions regarding translocation in addition to being an important component of viability. Population resilience will depend on successful dispersal.

6. Essential characteristics of refugia and adjacent, transitional zones, both natural upland and human-influenced.

A corridor or transition zone that serves an important ecological function for target organisms may also serve as corridor for a predator or an invasive/pest species. At the same time, transition zones can serve as conduits or barriers to dispersal (see #5, above).

7**. Information is needed on pollinators.**

More generally, what allows for connected subpopulations of plants in vernal pool and other priority habitat?

To address data gaps and sources of uncertainty noted above we recommend the following:

- **Encourage, support and update recommendations outlined in Chapter II with ongoing and innovative modeling and recalibration of climate change impacts.**

More specifically, the following is critically needed--the fruit of a next generation of landscape-wildlife-climate change models:

i. Better predictions of future environmental conditions including extreme events.
ii. Better information on tidal marsh restoration trajectory and how changing environmental conditions (as part of restoration) will affect wildlife and plants. Projecting change in marsh and tidal flats due to the climate, land-use decisions, and restoration need to be integrated.
iii. Develop better predictive models of population growth and persistence in future landscapes, subject to unpredictable events. Such models would be spatially-explicit, incorporate demographic processes, incorporate climate change impacts, and could be used to consider management alternative actions. Ideally, such models would identify population bottlenecks, control points.

We close with a final recommendation, related to data gaps and uncertainty:

- **Establish a comprehensive monitoring program.**

  A recommendation strongly urged by many workgroup participants is the establishment of a comprehensive monitoring program, in close coordination with other ongoing or planned efforts, including activities of the San Francisco Bay Joint Venture and the BAECC Climate Change Monitoring Project. In addition, a San Francisco Estuary Baylands monitoring program should be integrated with a Delta monitoring program, which is currently being developed.

  Proposing details of such a program is beyond the scope of the BEHGU project so no specific actions are proposed here. Clearly, not everything can be monitored all the time, but we believe that the 32 case studies included here provide a starting point, and that their authors can begin to outline a regional, responsive monitoring framework. A comprehensive monitoring program is critical to guide management. The monitoring program would assess:

1. Changes in population viability and species distributions, as they reflect climate change and anthropogenic impacts.

2. Effectiveness in achieving the goals of a management action, both immediate changes in the environment as well as the more long-term (often species-specific) goals with respect to target organisms.

3. Specific wildlife and plant response to management action.

Such a feedback loop of data from the field and management actions is the foundation of many of the wildlife-focused recommendations detailed in Chapter 2 of the main report – New Opportunities: How We Can Achieve Healthy, Resilient Baylands. Species easily monitored and representative of other members of their community allow cost-effective and informative monitoring of trends in populations and better inference into underlying influences on those trends. Assessing status and response of target species (such as threatened or endangered species) may be an ultimate goal, but to assess environmental conditions, how they are impacted by climate change, and how the biological community responds, will require monitoring additional species that may be especially informative. The broad-based monitoring of bayland species must be integrated with monitoring the drivers of environmental change at appropriate spatial scales, as well as including information on habitat and landscape features, such as characteristics of the transition zones, that affect the viability of plant and animal species. Thus monitoring of habitat quantity, quality, configuration, and important features of the landscape, as well as the physical drivers, is to be integrated with monitoring of plants and animals, reflecting our knowledge of how changes in the environment are impacting wildlife.

Rare and sensitive species are difficult to monitor but are at elevated risk due the episodic nature of many expected climate change impacts. A responsive monitoring program that includes such species is needed, integrated with the broad-based monitoring of trends. The rarity of these species makes it hard to discern changes in their condition on the basis of broad-scale monitoring alone, but rapid, informed management actions may be essential for assuring their long-term survival.

SUMMARY

Bayland plants and animals have evolved in the context of California's variable climate, across a landscape marked by dramatic changes in salinity and sea level. However, at present, suitable habitat has been severely reduced and remnant habitat is fragmented and degraded. Simultaneously, wildlife have been subject to an array of stressors such as contaminants, invasive species, human-associated predators (such as cats, crows, and gulls), loss of prey, unsuitable breeding conditions, and so on. Thus, the capacity of wildlife to adaptively respond to severe changes in habitat as well as to additional stressors, is already limited, and will be even more so in the future because: (i) future changes to habitat, due to climate change and land-use change, will occur at an accelerated pace, and (ii) extreme events, such as droughts, flooding, and storms, are expected to have increasingly severe impacts on wildlife.

Conservation of bayland plant and animal species in past decades focused on protection of individual populations in place, assuming stable vegetation structure and stable local environments. This assumption and conservation approach will be infeasible for the new sedimentary, submergence, storm, and salinity regimes of the 21st century estuary. To address these challenges we must focus on maintaining and promoting healthy, robust, interconnected populations, which are characterized by resilience in the face of dramatic changes in habitat and landscape configuration. Ensuring resilience means achieving high survival, reproductive success, and successful dispersal and recruitment of offspring into the adult population. For populations to be robust in the face of environmental change will require connectivity of habitat, on multiple time scales (daily, annual, decadal, etc.), and the ability of plants and animals to move effectively across the landscape, for example to colonize new habitat as it becomes available due to habitat restoration or climate change. Diversity within and among habitats is important, but it is especially important to sustain the dynamic processes that produce such diversity.

The long-term persistence of wildlife can be enhanced through management actions that reduce impacts of multiple stressors, thus increasing resilience to climate change impacts. Maximizing resilience entails enhancing recovery from catastrophic events (e.g., extreme storms) at the local scale as well as facilitating re-colonization of habitat where a species has previously been extirpated. Widely scattered, but connected, populations in appropriate habitats allow affected populations to recolonize or augment or "rescue" reduced populations. In species with limited mobility or with isolated habitats, translocations may be a necessary management action. Active and anticipatory management actions are needed to allow wildlife to weather the landscape-level changes and intensified stresses that climate change will bring to the San Francisco Estuary.

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SUPPLEMENTARY MATERIALS

Table S1. Summary of case study results.

Species or Group	Status	Bayland habitat, areas	Climate Change impacts	Other stressors, constraints	Sensitivity, Bottlenecks; other notes
Salt marsh harvest mouse	Endangered; trend not known. Higher numbers in some brackish areas.	Mainly tidal; also muted marsh; diked wetlands in Suisun. Throughout SFE; two subspecies.	Habitat loss; habitat fragmentation. Inadequate refugia from flooding, predation. Nest-flooding.	Loss of emergent vegetation or upland transitional zone (or very narrow band) a problem; Invasive plants.	Need tall and dense vegetation and/or upland refugia. Dispersal a limitation.
Shrews: Suisun and Salt marsh wandering shrew	Rare. Exception is Suisun shrew at Rush Ranch.	Tidal and diked marsh. Associated with marsh-terrestrial ecotone.	Flooding leading to food shortage. Habitat loss.	High overall mortality. Contaminants.	Little population data. Species survival depends on protection and expansion of ecotone.
River otter	Increasing; no special status	Creeks and reservoirs throughout SFE	Loss of denning habitat; change in prey due to change in salinity	Pathogens	Piscivores. Quite mobile. Populations not well-studied.
Harbor seal	Stable or increasing	Tidal rock, mudflats; throughout SFE	Loss of habitat for resting and nursing pups critical; shifts in prey, predators or pathogens	Disturbance, contaminants, disease	Sensitive to shifts in prey and to disease (especially to pathogens not previously encountered like phocine distemper virus)
Ridgway's rail	Federally Endangered; short-term decrease, increasing since 1990's	Saline tidal marsh; Central and South SF Bay; San Pablo Bay	Habitat loss and alteration; Inundation. Leading to nest failure and high predation	Human-associated predators. Affected by control of invasive Spartina.	Vegetative cover important. Need "in-marsh" refugia.
Song sparrow	Decline; species of special concern	Tidal marsh (and muted tidal); throughout SFE	Habitat loss and alteration; inundation from SLR and storms; shorter breeding season due to temp, precipitation	Nest-predation high (multiple predators)	Need to address low nest survival
Black rail	State threatened; increasing	Mid- to high-tidal marsh. In SFE except in South SF Bay.	Marsh inundation due to SLR and storms, in winter and spring. Leading to lower survival, reprod success	Invasive plants; predation by non-native predators; human disturbance; habitat fragmentation	Low dispersal; little known about this. Winter habitat requirements not known.

Northern harrier	Trend not known. Common.	Multi-habitat generalist. Throughout SFE.	Loss of habitat due to SLR; inundation of nests	Nest predation (foxes); contaminants (including lead)	Representative raptor in bayland habitat. Rely on upland habitat (affected by changes to that).
Shorebirds: American avocet and **Western sandpiper (WESA)**	WESA: apparent decline (or just shift). Neither species has special status.	Avocet: managed ponds and tidal marsh; breeder. WESA: tidal flats, winter-resident.	Loss of habitat (mudflat for WESE); prey may change, shift.	WESA: low reproductive rate. Avocet: low chick survival. Nest predation high.	WESA: vulnerable due to complex migration, not flexible; loss of managed ponds with high prey biomass. Avocet: California gulls a problem.
Terns: Forster's (FOTE) and **Least (LETE)**	LETE: Federally Endangered; FOTE: may be declining	LETE: breed on beaches, islands. Only a few locations. FOTE breed in marshes.	Fluctuation in prey (LETE: anchovy important). Water level affects nest success.	Mercury severe problem, causes egg, chick mortality	Most FOTE breed in former salt ponds, on islands.
Dabbling ducks: multiple species	Mostly increase in Suisun and San Pablo; pintail decrease	Managed wetlands, managed ponds . Winter throughout SFE; some breeding, in Suisun.	Reproductive success declines with temperature; salinity	Disturbance a concern; conditions on staging areas important; winter and spring habitat can influence reproductive success	Loss of diked/ managed wetland a concern (e.g., due to restoration); salinity can affect vegetation and invertebrate prey
Diving ducks: multiple species	Some species declining. No special status spp.	Open bay, managed ponds; mainly winter, throughout SFE	Loss of habitat due to SLR; change in prey distribution	Energetic (prey) constrained; disturbance, contaminants. Effects on breeding grounds	Herring roe very important for scoters; foraging depth important
California toad	Western toad declining; Calif. subspecies not known, common	Breed in freshwater; need upland refugia nearby. Throughout Bay Area.	Will be impacted by increase in temperature, salinity; decrease	Pathogens, UV-B radiation, salinity	Dispersal can be issue
California Red-legged frog	Fed. threatened; range has contracted	Tidal (brackish) marsh; breed in freshwater ponds	Inundation, storms; Salinity, Loss of habitat	Egg and larval survival extremely low; predation	Very sensitive to salinity. Limited by dispersal (need fresh ponds near marsh).
Pacific herring	Recent increase, after recent collapse	Shallow aquatic, North bay	Salinity shift away from spawning substrate	Ocean conditions, harvest	SF Bay one of few spawning sites. Economically valuable
Delta smelt	Drastic decline	Limited, Suisun and delta	Spawning window, Delta outflow	Entrainment, food web, predation	Very limited distribution; No other population. Sensitive.
Longfin smelt	decline	Limited, Suisun and San Pablo	Spawning conditions	Entrainment, food web, predation	Population in Washington State and maybe North

					Coast
Longjaw mudsucker	decline	Pickleweed marsh widespread	Habitat loss, desiccation	unknown	Common elsewhere; limited range makes good local indicator
Tidewater goby	extirpated	Estuarine lagoons San Pablo	Re-establish?	Invasive species	In some coastal lagoons, including nearby
Grunion	extirpated	Sandy beach North bay	Re-establish?	Human disturbance	Re-established briefly 2000-08; El Nino may facilitate
Chinook salmon and **steelhead**	decline	Vegetated Edge, widespread	Upstream thermal stress	Ocean conditions, upstream conditions	River and estuary most important when ocean less productive
Dungeness crab	increasing	Shallow aquatic, marsh channels, eelgrass, widespread	limited	Ocean conditions,	Economically valuable; mobile and widespread; good broadscale indicator species
Marsh invertebrates: many	Various.	All parts of tidal marsh (including channels); throughout SFE.	Loss of habitat due to SLR, particularly loss of high marsh. Change in temperature and vegetation could affect invertebrates.	Invasive pepperweed an issue.	Some insects can tolerate inundation. These invertebrates not well studied. Important as prey for vertebrates. Depend on plants, phenology.
Vernal Pool	Rare. Includes plants, crustaceans, other inverts; amphibians.	Freshwater, ephemeral pools.	SLR will lead to habitat loss; saltwater intrusion. Increased temperature and decrease in precipitation reduce inundation periods.	Little remaining habitat; Isolated ponds	Manage for variety of pool size and depth.
Spartina, Native and Invasive	Native: wide spread, Invasive: Recent; nearly removed at present	Invasive: Most problematic in Central and South SF Bay; potential problem in San Pablo	Higher salinity and more inundation favor the invasive/hybrid.	Hybrid is very invasive. Control can be difficult. Invasive control can have impact to Ridgway's Rails.	Native is foundational species. Invasive responsible for major, physical alteration of habitat, loss of diversity.
Submerged Aquatic Vegetation	Widespread but only locally abundant. Possibly increasing in Suisun Bay subtidal habitat	Low turbidity shallow subtidal aquatic habitat (shallow bay, slough), sheltered marsh ponds, lagoons	Low turbidity (reduced suspended sediment concentration) favors increase growth;	High (polyhaline-euhaline) salinity favors only 1 genus (*Ruppia*), restricts range of both native	Unrepaired levee failure of diked subsided baylands may increase habitat as sea level rises. High wave energy at shoreline (marsh

				and non-native pondweeds (*Stuckenia, Potamogeton* spp.)	peat erosion) and SLR may increase habitat. Increase of wigeongrass and pondweed; rapid change in relative abundance with seasonal salinity patterns is expected
Low Tidal Marsh Plants (grasses, sedges, tules)	Widespread; Foundational species. Few tall emergent species tolerate deep tidal flooding and dominate low marsh	Cordgrass dominates polyhaline-euhaline low marsh (to approximate MSL); tules, bulrushes, cattails, sedge dominate oligohaline to mesohaline low marsh (to approximate MLW)	SLR will likely convert intertidal marsh plains to transitional low-middle marsh zone or low marsh. Higher salinity during growing season favors cordgrass over tule, bulrush, sedge	Higher wave energy due to deepening bays (SLR) may restrict low marsh to wave-sheltered sloughs. Higher wave energy and salinity may expand cordgrass marsh with altered structure and ecogeomorphic function (selection for hybrid *Spartina alterniflora* traits in backcrossed populations)	High seed production, dispersal ability, rapid potential colonization of suitable salinity & disturbance regimes
High Tidal Marsh Plants: annual forbs and graminoids	Many reduced to rarity, with few & mostly isolated, small populations; reduced geographic range within Estuary	Mostly in or near remnant prehistoric tidal marshes in high marsh & transition zone	SLR will likely increase submergence of existing habitat (convert to middle marsh); constrained potential for new habitat to support populations	Mostly limited dispersal ability (broadleaf annual forbs), adapted to local dispersal in favorable, specialized sub-habitats	Most spp. have low potential seed dispersal. Potential rapid colonization of restored high marsh and transition zone habitat (assisted migration) with suitable structure (gaps or reduced competition with dominant perennials)
High Tidal Marsh Plants: subshrubs and perennial forbs (including T/Zone)	Many spp. still common in brackish marshes, esp. N Estuary; only gumplant common in salt marsh today	Mature high brackish to salt marsh and lower terrestrial transition zones with complex soil and hydrologic gradients, and mature tidal channel banks (natural levees, well-drained bank edges)	Loss of habitat (high marsh submergence, erosion), increased frequency of marsh hypersalinity events (droughts)	Low tolerance of soil waterlogging; low to moderate salinity tolerance in most spp. Limited seed source populations in modern salt marshes (SFB)	Many species, high diversity, in relatively narrow but complex marsh edges with gentle gradients. Often associated with to mature or prehistoric tidal marsh remnants; limited extent and distribution, rarely

					restored.
High Tidal Marsh Plants: perennial graminoids (including T/Zone)	Many spp. still common in brackish marsh; only saltgrass common in salt marsh today	Mature high brackish to salt marsh plains to transition zones with complex soil and hydrologic gradients	SLR-induced submergence, increased frequency of marsh hypersalinity events (droughts); competition with more tolerant pickleweed; slower to recolonize than pickleweed	Limited seed source populations in modern salt marshes (SFB)	Often associated with mature or prehistoric tidal marsh remnants with peaty or sandy high marsh zones near seed source populations.
Terrestrial/Marsh Ecotone Graminoid **Plants** (Grasses, sedges, rushes; Transition Zone)	Few remnant or regenerated populations of perennial, sod-forming creeping grass, rush, sedge species bordering northern Estuary	Clayey to sandy loams on seasonally wet gentle slopes, above highest tide lines to spring high tide line	Frequent levee maintenance limits colonization and establishment.	Seed limitation of founder populations due to isolated and relatively small remnant populations. Cattle trampling and overgrazing destroys rhizome networks and reduced populations at tidal marsh edges	Increases following reduction of cattle trampling frequency. Low long-distance dispersal ability, high short-distance dispersal ability (clonal spread). Populations can regenerate following cessation of cattle trampling/overgrazing
Terrestrial/ Marsh Ecotone Plants **psammophytes: sand plants** (Transition Zone)	Mostly extirpated due to historic loss of sandy tidal marsh transition zones; one sand-specialized endangered species reintroduced locally	Marsh-fringing barrier beaches, San Pablo Bay, Central SF Bay (historic core habitat) S Bay; some persistent or regenerated habitats provide refuge	Continued loss of habitat and coarse sediment (urban shoreline armoring, wave erosion in response to SLR)	Increased wave energy and erosion potential with deeper bay (SLR), reduced coarse sediment supply (armoring)	Potential for rapid recolonization of restored habitat by some common species; artificial reintroduction needed for rare species. Iceplant, perennial pepperweed can rapidly invade habitat