POTENTIAL IMPACTS OF CLIMATE CHANGE ON BIODIVERSITY AND ECOSYSTEM SERVICES IN THE SAN FRANCISCO BAY AREA

Prepared for: California Energy Commission
Prepared by: University of California, Berkeley

JULY 2012
CEC-500-2012-037

David D. Ackerly[1]
Rebecca A. Ryals[1]
Will K. Cornwell[1]
Scott R. Loarie[2]
Sam Veloz[3]
Kelley D. Higgason[4]
Whendee L. Silver[1]
Todd E. Dawson[1]

[1] University of California, Berkeley, California
[2] Carnegie Institution for Science, Stanford, California
[3] PRBO Conservation Science, Petaluma, California
[4] National Oceanic and Atmospheric Administration, San Francisco, California

CALIFORNIA
natural
resources
AGENCY

DISCLAIMER

ACKNOWLEDGEMENTS

R. Moe, R. Cameron, R. Shaw, S. Beissinger, D. Lindberg, M. Santos, D. Wake, and A. M. Merenlender contributed information and comments on the manuscript that improved this paper.

ABSTRACT

The San Francisco Bay Area contains a rich array of plant and animal biodiversity and an extensive open space network, embedded within a major metropolitan area. Terrestrial habitats in the San Francisco Bay Area support a wide range of ecosystem services, including carbon storage, forage production, enhanced water supply and quality, crop pollination, and outdoor recreation. The distribution of habitats and plant and animal species is strongly influenced by spatial variation in climate, and is thus expected to change in response to changes in regional and global climate. Current research suggests that most vegetation types will shift toward the coast, especially under scenarios with warmer and drier conditions; range contractions and reduced diversity are projected for California endemic plants in the Bay Area. Bird communities are projected to undergo significant reorganization, leading to altered interactions and community structure. Improved modeling at fine spatial scales represents an important priority to reduce uncertainty in these projections.

Climate change is expected to strongly affect ecosystem services. Carbon storage in soils and vegetation could contribute to California’s carbon emissions reduction strategy, but current models project reduced carbon storage in trees due to climate change. Altered agricultural management strategies, including conversion to perennial crops, have the potential to increase soil carbon storage. Climate change impacts on vegetation, hydrology and habitat integrity may negatively affect fire regimes, forage production, water supplies, crop pollination services, and outdoor recreation and quality of life in the San Francisco Bay Area, but few specific projections are available.

Strategic conservation planning in the Bay Area is under way to enhance biodiversity conservation through continued open space acquisition. Conservation of heterogeneous landscapes will provide resilience in the face of climate change. Improved understanding of projected climate change impacts on natural habitats will contribute to the development of regional adaptation strategies.

Keywords: biodiversity, vegetation, ecosystem services, San Francisco Bay Area, climate change adaptation, protected areas, spatial heterogeneity

Please use the following citation for this paper:

Ackerly, David D., Rebecca A. Ryals, Will K. Cornwell, Scott R. Loarie, Sam Veloz, Kelley D. Higgason, Whendee L. Silver, and Todd E. Dawson. 2012. ***Potential Impacts of Climate Change on Biodiversity and Ecosystem Services in the San Francisco Bay Area.*** California Energy Commission. Publication number: CEC-500-2012-037.

TABLE OF CONTENTS

LIST OF FIGURES

Section 1: Introduction

The San Francisco Bay Area (SFBA) is recognized as a hotspot of biodiversity within California and at a national scale (Myers et al. 2000). This diversity is supported by sharp climate gradients, rugged topography, and heterogeneous soils. Natural ecosystems in the SFBA also represent valuable "natural capital" for the region, providing a wide range of ecosystem services, including improved water quality and supply, carbon sequestration, pollination services, outdoor recreation, and enhanced quality of life for a large urban and suburban population.

The objective of this paper is to summarize the current state of research on the potential impacts of anthropogenic climate change on SFBA biodiversity and ecosystem services. Studies addressing climate change include observational, experimental, and modeling approaches. Variability of natural ecosystems across spatial gradients provides important insights into how natural ecosystems respond to climate, and may respond to climate change given enough time to equilibrate. Historical data can provide evidence of response to past climate change, though these changes have rarely if ever proceeded as rapidly as those forecast in the next 100 years.

This paper focuses on terrestrial habitats, with brief discussions of intertidal wetlands and coastal and nearshore environments. In terrestrial systems, the impacts of rising temperature and changing precipitation patterns have received the most attention, along with nitrogen deposition, direct and indirect effects of elevated carbon dioxide (CO_2), and changing fog cover. In estuarine and intertidal areas, sea level rise is the most important direct impact (see accompanying paper by Heberger et al. (2012) addressing impacts of sea level rise on coastal infrastructure). Climate change impacts on freshwater fish are addressed in the accompanying paper by Moyle et al. (2012). The aquatic ecosystems of San Francisco Bay are not addressed in the current SFBA vulnerability analysis, and merit attention in future analyses.

1.1 Climate and Biodiversity in the Bay Area

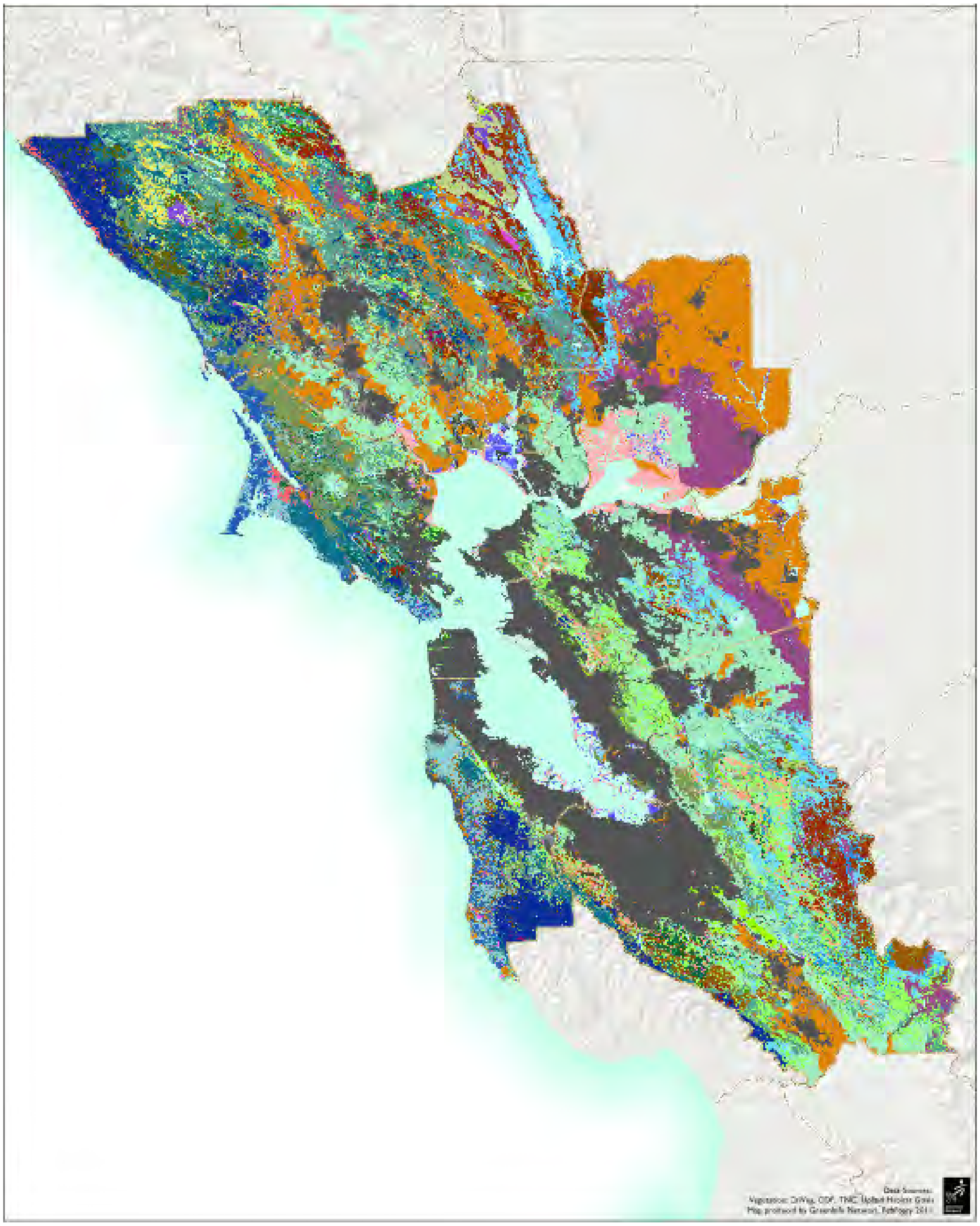
Plant and animal diversity and distributions in the SFBA are strongly influenced by climate gradients. The most important of these are the coastal-inland gradient in temperature (including fog frequency and the inland penetration of the marine layer around San Francisco Bay), elevational gradients on local mountain ranges, and distinct rain shadows on the eastern slopes of the Inner and Outer Coast Ranges. A recent high-resolution map of SFBA vegetation distinguishes more than 25 major native vegetation types,[1] from interior grasslands to coastal redwoods (Figure 1). The distribution of major vegetation types is strongly influenced by the climate gradients identified above, as well as local topographic effects due to solar radiation (south vs. north-facing slopes), cold air drainages, wind on exposed ridges, and a complex mosaic of different soil types. The upwelling of cold waters along the coast supports highly productive marine ecosystems, and these resources contribute to terrestrial diversity as well (especially birds).

The SFBA sits near the center of the California Floristic Province, defined by the distinctive Mediterranean-type climate and running from southern Oregon in the north to Baja California

---

[1] Bay Area Open Space Council (2012) The Conservation Lands Network, http://www.bayarealands.org/

in the south, and east to the Sierra Nevada. The floristic province contains more than 5000 native plant taxa, of which almost half are unique (endemic) and found nowhere else (Hickman 1993). The Bay Area alone has about 3000 native plant taxa, and over 50 locally endemic species or subspecies (Figure 2). Endemics include the unusual western leatherwood (*Dirca occidentalis*), a number of manzanitas (*Arctostaphylos spp.*), and a variety of flowering forbs. Two plants that were thought to be extinct in the wild were recently rediscovered: the Presidio manzanita (*Arctostaphylos franciscana*), found growing in a clump of eucalypts in the San Francisco Presidio, and the Mt. Diablo buckwheat (*Eriogonum truncatum*).



Data Sources:
Vegetation: CalVeg, CDF, TNC, Upland Habitat Goals
Map produced by GreenInfo Network, February 2011

Figure 1. Vegetation Map for the San Francisco Bay Area, Illustrating the High Degree of Habitat Heterogeneity and Proximity of Urban Areas and Open Space

Source: Map courtesy of Bay Area Open Space Council 2012.
http://www.bayarealands.org/gis/download/Vegetation_032411.pdf

Figure 2. Landscapes and Distinctive Plants and Animals of the San Francisco Bay Area. (A) Coastal grasslands and Douglas fir forests in Mt. Tamalpais State Park above Stinson Beach. (B) Grasslands, oak woodlands and chaparral, looking NW from Mt. Diablo State Park; fog over the bay and delta in background. (C) Northernmost stand of Coulter pine, *Pinus coulteri*, at Black Diamond State Park, with the Delta in the distance. (D) Sonoma Co. endemic *Lasthenia burkei* (all yellow) and *Layia platyglossa* (white tipped petals), Santa Rosa. (E) Bay checkerspot butterfly, *Euphydryas editha bayensis*. (F) California Clapper Rail, *Rallus longirostris obsoletus*.

Photo credits: A–D, D. D. Ackerly; E, S. B. Weiss; F, K. Navarre.

The SFBA supports a remarkable diversity of terrestrial animals. These include large mammals such as mountain lion (*Puma concolor*), black bear (*Ursus americanus*), and Tule elk (*Cervus candensis nannodes*), as well as less charismatic, but regionally noteworthy, taxa such as the endangered Salt Marsh Harvest Mouse (*Reithrodontomys raviventris*) and the unique Point Reyes mountain beaver (*Aplodontia rufa phaea*). San Francisco Bay itself, as the largest estuary on the West Coast, supports large numbers of migratory and wintering shorebirds and waterfowl, and the largest populations of the endangered Clapper Rail (*Rallus longirostris obsoletus*) and threatened Black Rail (*Laterallus jamaicensis)* in the west. The SFBA also supports three unusual state-listed subspecies of Song Sparrows (*Melospiza melodia*). The Bay Area's old-growth redwoods support the southernmost populations of the endangered Marbled Murrelet (*Brachyramphus marmoratus*, in Big Basin) and Northern Spotted Owls (*Strix occidentalis caurina*, in Marin County). The SFBA is also an important hotspot of amphibian diversity, including threatened Yellow-Legged frogs (*Rana boylii*) and California Tiger salamanders (*Ambystoma californiense*). Several amphibian lineages exhibit hotspots of genetic diversity in the Coast Range south of San Francisco Bay, reflecting patterns of evolutionary diversification and the influence of the region's complex geological history (Martínez-Solano et al. 2007; Kuchta et al. 2009).

Over the past half-million years, climatic fluctuations from colder and drier glacial eras to warmer, wetter interglacials (which we are in now) have had profound effects on Bay Area plants and animals. A pollen diagram from Clear Lake (Lake County) shows a rapid transition from cedar- and pine-dominated vegetation to oak between 17,000 and 15,000 years ago (Adam 1988), similar to the pace of transition observed in many other parts of North America and Europe at the end of the last ice age. During glacial periods, when sea level was lowered by up to 120 meters (m), the coastline in the Bay Area moved westward to just beyond the current Farallon Islands. At these times, San Francisco Bay was a large, interior valley, presumably supporting extensive grasslands and forest, with a wide riparian corridor along the Pleistocene San Francisco River. When sea level rose, the estuaries of the bay would have been repopulated by aquatic life and wetland vegetation. This process of emptying and refilling portions of the bay has apparently occurred more than 40 times during the past 250,000 years, most recently filling just 8000 years ago (Sloan 2006). When the bay is full, it has created a barrier to dispersal and gene flow for many terrestrial taxa, evidenced by phylogeographic breaks in population genetic data (e.g., *Dirca occidentalis*; Graves and Schrader 2008). These patterns demonstrate the importance of relatively rapid climate-driven transitions in plant and animal life over periods of thousands to tens of thousands of years, similar to those observed throughout the Northern Hemisphere over this time period (Graham 1999).

Roughly 13,000 years ago (if not before), Native Americans arrived in coastal California. Native Americans profoundly altered the California landscape by harvesting and hunting, and extensive burning of pastures (Broughton 2004; Anderson 2006; Minnich 2008). Burning may have stimulated germination and regrowth of edible forbs, and also increased deer forage. Presumably many such fires would have spread into adjacent shrublands and woodlands, potentially affecting vegetation distributions throughout coastal California. Recent research suggests that the open pastures of coastal California were originally dominated by flowering forbs, with a less important contribution of native bunchgrasses than has long been assumed (Minnich 2008). The arrival of the Spanish brought intensive cattle grazing to California, and the introduction of European alien plants, many of which rapidly invaded native vegetation. Most important, European annual grasses replaced the native grasses and forbs of California's pastures and open oak woodlands. The legendary "golden hills" of modern California are the dry stems of the short-lived annuals, and these fast-growing plants take up water rapidly in spring, resulting in drier summer soils (Chiariello 1989). More than 500 alien plant species are now established out of cultivation in California with ranges including the Bay Area. Invasives that profoundly influence local communities include ice plant (*Carpobrotus edulis*), yellow star thistle (*Centaurea solstitialis*), true thistles (*Circium* spp.), scotch broom (*Cytisus scoparius*), gorse (*Ulex* spp.), and eucalypts (*Eucalyptus* spp.). Native Americans and Europeans had profound impacts on animal populations as well, through habitat transformation and direct effects of hunting (e.g., Broughton 2004).

With the gold rush and the ensuing rapid development of California (which has continued unabated to the present day), the Bay Area was rapidly transformed by logging for timber, bark, and charcoal, the growth of the wine industry and other types of agriculture, and most important, by population growth and urbanization. As in other coastal zones, development has been concentrated around the coastline and the Bay, leading to large-scale transformation of estuaries and salt marshes. At the same time, San Francisco served as the heart of California's conservation movement, through its intimate role in conservation battles in the Sierra Nevada and early efforts in local land conservation. Big Basin Redwoods State Park (Santa Cruz County) became the first State Park in 1902. Portions of Mt. Tamalpais, Mt. Diablo, the East Bay hills and other parcels were acquired for conservation prior to 1950, though formal protection came later in many cases. Large watersheds were set aside surrounding local reservoirs, some storing Sierra Nevada water in transit to the cities, such as Crystal Springs (San Mateo County) and Calaveras Reservoir (Santa Clara County). Development battles in Marin and Sonoma Counties in the 1960s and 1970s led to the creation of numerous smaller parks and the preservation of extensive open space and agricultural land (Griffin 1998). These efforts culminated in the creation of Point Reyes National Seashore, one of the largest parks in close proximity to a major metropolitan area in the United States. In addition, the military kept large expanses off limits to development, from the Presidio through the Marin Headlands, and much of this land has now been converted to open space for public recreation.

As a result of these efforts, and many others by local, state, and federal agencies, as well as non-governmental organizations and private landowners, approximately 25 percent of the Bay Area's 4 million acres are set aside in protected open space, either in fee title or under conservation easements (Bay Area Open Space Council 2011). Another 25 percent are urbanized, and approximately 50 percent are in working landscapes or natural vegetation that lacks formal protection. The mild climate and the accessible open spaces of the Bay Area are vital to the quality of life and the recreational activities of the region, representing a valuable component of the area's natural capital that is supported by native (and in some cases alien) biodiversity. The San Francisco Bay Area, together with Cape Town, South Africa, probably represent the greatest concentrations in the world of native biodiversity in such close proximity to major metropolitan areas.

This brief history of the transformations of land use and biodiversity in the Bay Area provides a context to consider potential climate change impacts and climate adaptation strategies. Ecological communities are highly dynamic, and can be altered and transformed by changing climate, wildfire, biological invasions, and human impacts. It is very difficult to identify the "natural" state of the Bay Area's ecosystems prior to European arrival, and even more so prior to Native American impacts. In the face of profound changes in climate, the primary challenge in the Bay Area will be to manage for continued ecological change that fosters biodiversity conservation and ecosystem services.

1.2 Climate Change Projections for the Bay Area

Climate change projections for the Bay Area are available from many different modeling efforts, including high-resolution Regional Climate Models (RCM; e.g., Snyder and Sloan 2005) and spatially downscaled output from General Circulation Models (GCM; e.g., Hayhoe et al. 2004; Maurer et al. 2007). As part of the California Energy Commission's vulnerability analysis, Cayan et al. (2012) summarized output from six GCMs and two emissions scenarios, at a scale of 12 kilometers (km), over the Bay Area. Depending on the climate model and emissions scenario, mean annual temperatures for the region are projected to increase between 2°C and 6°C (3.6°F and 10.8°F) by the final decades of the twenty-first century, with greater warming in summer (Cayan et al. 2012). Warming will be somewhat stronger in interior regions than in coastal regions, exacerbating the existing spatial temperature gradient. Areas around the Bay that have experienced annual frosts in the past are projected to be frost free in at least some years (Ackerly 2012). The winter rainfall regime will be maintained, with high interannual variability in total precipitation; most simulations project a slight drying trend over the course of the century, but there is high variability among models. Sea level rise is expected to reach 55 to 130 centimeters (cm) (22 to 51 inches) above current levels by the end of the century.

Climate change projections obtained from GCMs are based on coarse spatial grids, often at 2° latitude and longitude, while those from RCMs are at finer scales (e.g., 40 km for Snyder and Sloan 2005). For many biological applications, finer spatial resolution is needed through downscaling of future projections onto high-resolution historical climate surfaces (e.g., 1 km PRISM[2] climatologies). Recently, Flint and Flint (2012) have developed an intensive downscaling methodology, with a focus on landscape hydrology, to obtain spatial surfaces for current and future climates at a 270 m scale, and these are being employed in a new generation of biological impact studies (e.g., Micheli et al. 2010). Methods for spatial downscaling are the subject of considerable debate. While the details are beyond the scope of this paper, readers should be aware that studies of biological impacts (including those summarized in this paper) may use different climate change projections and different downscaling methods, rendering direct comparisons difficult.

Discussions of climate change projections and impacts are based on a range of scenarios for future greenhouse gas emissions and global socio-economic development considered in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007). The most frequently discussed scenarios include B1, based on significant reductions in greenhouse gas emissions during this century, and the A2 or even higher A1FI scenarios, with continuing rapid increases in emissions (Solomon et al. 2007). It is important to recognize that in the past decade, the observed trajectories of greenhouse gas emissions have exceeded the highest emissions scenarios considered by the IPCC (Raupach et al. 2007), so "worst-case" outcomes may be increasingly likely. The Fifth Assessment Report of the IPCC is expected in 2013 and 2014, and will provide updated emissions scenarios and climate projections that will become the basis for future research and decision making.

---

[2] Parameter-elevation Regressions on Independent Slopes Model

Section 2: Projected Impacts of Climate Change on Biodiversity

2.1 Distribution of Major Vegetation Types and Terrestrial Habitats

In general, Bay Area vegetation consists of coniferous forests (redwood and Douglas fir) in the coolest and wettest environments (including areas of high fog influence); oak and other evergreen woodlands on deep soils and areas of high rainfall; shrublands on hotter and drier sites, especially steep slopes with thin soils; and grasslands scattered across the region under a wide range of climate conditions. The influence of maximum summer temperatures versus minimum winter temperatures on these distributions is not well understood. This is important because these two factors are negatively correlated in space (warmer winters and cooler summers near the coast), and both winter and summer temperatures will rise with future climate change. Soil moisture availability plays a critical role in vegetation distributions; increased temperatures will cause enhanced evapotranspiration and overall trends toward reduced soil moisture, even for future climate scenarios with increased precipitation (see Micheli et al. 2010).

Several modeling studies have projected impacts of climate change on California vegetation, including the Bay Area (Lenihan et al. 2003; Stralberg et al. 2009; Shaw et al. 2009). These models, and other work currently under way, generally forecast a reduction in the extent of coniferous and evergreen broadleaf forests and increases in oak woodlands, shrublands, or grasslands. One exception to this general pattern is a forecast for increased forest in the North Bay for future climate scenarios that predict increased precipitation (Lenihan et al. 2003). While a detailed discussion of modeling methods is beyond the scope of this paper, it is important to note the assumptions and approaches used to generate forecasts for future species and vegetation type distributions. For vegetation distributions, two approaches have been used in studies covering the Bay Area.

Lenihan and colleagues (2003; Shaw et al. 2009) have used the MC1 dynamic vegetation model, which incorporates both mechanistic and statistical approaches to model the productivity, growth, and susceptibility to fire for major vegetation types: evergreen conifer forest, mixed evergreen forest, mixed evergreen woodland, grassland, and shrubland. Early work was run on 100 square kilometer (km^2) pixels (Lenihan et al. 2003), while current studies (unpublished) are being run at 0.64 km^2 and will provide a much finer resolution of potential vegetation distributions. The major advantages of the approach in the MC1 model is the basis in physiological and biogeochemical mechanisms, while the most significant disadvantage is the coarse resolution of vegetation types, limiting the ability to draw broader inferences about biodiversity impacts.

The second class of models, used for vegetation and species modeling, is based on statistical modeling of the associations among vegetation types and climate variables, and projection of these models into the future. A wide variety of statistical methods have been introduced for this problem, varying in the type of input data that is needed and the underlying statistical methods (see Elith et al. 2006; Elith and Leathwick 2009). Stralberg et al. (2009) used the "random forests" algorithm to project shifts in dominant plant communities, providing the vegetation base layer for their modeling of bird communities. Random forests is an extension of classification tree methods that find the optimal series of bifurcations in predictor variables (e.g., climate, soils) to classify the observations in the dependent variable (vegetation types). A strength of classification trees is their ability to handle arbitrary interactions and nonlinear patterns, though this also can be a drawback as the resulting models can have many parameters and may not be easy to interpret. More recently, Cornwell et al. (2012) have adapted the method of multinomial logistic regression for predictive vegetation modeling. This approach is unique in simultaneously modeling the entire suite of vegetation types as a vector of relative probabilities for each site in the landscape. However, it is also difficult in this case to extract easily-interpretable parameters that can be related to underlying mechanisms for individual vegetation types.

A key limitation shared by all models of community and vegetation type distributions is the assumption that the currently observed types will persist into the future (Ferrier and Guisan 2006). Models of existing vegetation types do not allow for non-analog communities composed of new combinations of existing taxa, or for novel types invading from outside the study domain. This problem can be addressed in part through models of individual species responses (see below). All modeling studies are also limited in their ability to make projections under novel climates, i.e., future climate conditions that fall entirely outside the range of conditions that occur within the modeling domain in the present day. And finally, a critical assumption of the models is that current distributions are in equilibrium with recent historical climate, and that future vegetation distributions will equilibrate immediately to future climate change. Rapid climate change may cause transient effects that are not captured in equilibrium models, and vegetation responses to twenty-first century climate change depend on dispersal rates, biotic interactions, and successional dynamics, and may continue for hundreds or thousands of years.

Based on the different modeling studies, potential impacts can be examined for vegetation types of special interest. Oak woodlands provide critical habitat for wildlife and are a distinctive feature of the SFBA landscape, but current research does not provide a clear consensus on potential climate change impacts. There are six oak species that form the dominant vegetation in different parts of the SFBA—coast live oak (*Quercus agrifolia)*, interior live oak (*Quercus wislizenii)*, blue oak (*Quercus douglasii)*, canyon live oak (*Quercus chrysolepis)*, valley oak (*Quercus lobata)*, and black oak (*Quercus kelloggii)*. Kueppers et al. (2005) modeled the responses of *Quercus lobata* and *Quercus douglasii* using a 4 km spatial grid and projections from a regional climate model. Their model suggested that suitability for both species is declining in the SFBA, especially on the eastern edge for currently suitable habitat for each species (where current summer temperatures are highest). Finer-grain models are less pessimistic for oak forest (modeling all oak forest as one entity at an 800 m grid resolution; Stralberg et al. 2009), with decline in the East Bay partially offset by invasion of more mesic sites in the North Bay.

Figure 3. (A) Redwood Grove, Big Basin State Park. (B) Redwood Distribution in Bay Area.

Source: Photo D. D. Ackerly. Map courtesy of Save the Redwoods League.

The fate of redwood forests is also of special concern, both for their contribution to ecosystem services and their iconic identity as the world's tallest tree (Figure 3). There has been a great deal of recent physiological and ecological study on the species and its environment (Burgess and Dawson 2004; Corbin et al. 2005; Burgess et al. 2006; Fischer et al. 2008; Simonin et al. 2009; Mullin et al. 2009). However, there is not currently a consensus about the fate of the species in the Bay Area as it relates to climate change. In large part this is because the interception of fog is well known to be a crucial resource for the species (Ingraham and Matthews 1995; Dawson 1998; Burgess and Dawson 2004; Simonin et al. 2009; Limm et al. 2009; Ewing et al. 2009), and the future frequency of fog is unknown. The record from airports since 1951 indicates a trend toward less fog (33 percent less today than in 1951; Johnstone and Dawson 2010), and a greater decline is inferred from temperature records since 1900.

In their analyses of hourly coastal versus inland temperature data from over 100 weather stations, Johnstone and Dawson (2010) also show that that the coast has been warming faster than the inland for the past 60 years. This leads to a lower coastal-inland temperature difference that is likely to be the reason advection fog has also declined (the coastal-to-inland "pull" has lessened). In contrast to this result, temperature observations from coastal weather stations in Los Angeles and San Francisco during 1970 to 2005 suggest cooler summer temperatures (Lebassi et al. 2009), and modeling efforts based on these temperature records suggest the potential for increasing upwelling, which may lead to more frequent summer fog (Snyder et al. 2003). Clearly, refinements to modeling fog are needed. A climate envelope modeling approach that did not include fog explicitly suggested marked declines of redwood forest in the Bay Area

(Stralberg et al. 2009), and such declines would presumably be exacerbated if there was a continued decline in fog cover as well.

The distribution and climate impacts on Bay Area annual grassland represent a special problem. European settlers brought a large number of exotic species to California, many of which became naturalized or invasive, creating the modern annual grassland vegetation. Most of the problematic species were introduced in the nineteenth century, and by the 1860s–1880s, most grasslands were dominated by exotic annual grasses (Minnich 2008). At present, grasslands are not confined to a particular climate-topographic niche within the Bay Area. Rather, a nexus of climate, topography, and land use determines whether a given plot of land is grassland or woody vegetation. Detailed local studies suggest that both herbivory (by black-tailed deer [*Odocoileus hemionus*] and cattle) and the drawdown of water in the shallow soil layers by the fast-growing grasses is important in preventing invasion by woody plants (Davis and Mooney 1985). The MC1 model suggests that grasslands will expand on the eastern edge of the SFBA due to increased summer temperatures (Shaw et al. 2009). Against this general trend, it is expected that there will be highly local effects of land use and herbivory on the future of individual parcels.

2.2 Distribution and Diversity of the Endemic Flora

Loarie et al. (2008) modeled the impact of future climate change (through 2070–2099) on the distribution of California's endemic plants. Their study, like that of Kueppers et al. (2005, discussed above), modeled individual taxa and thus does not make any assumptions about the stability or distribution of vegetation types. Loarie et al. employed the popular Maxent modeling algorithm (Phillips et al. 2006), which is particularly effective when dealing with sparse, presence-only observational data available from field observations and museum or herbarium specimen data (Elith et al. 2006).

This study explored two emission scenarios. The first is the higher SRES A1FI scenario, with global CO_2 emissions reaching almost four times present-day levels by 2100. The second emissions scenario, SRES B1, is lower, with CO_2 emissions rising slightly by mid-century before dropping to below present-day levels by the end of century. They also explored results from two global climate models with higher and lower sensitivities to atmospheric greenhouse gas levels. The U.K. Meteorological Centre's Hadley Centre Coupled Model version 3 (HadCM3) model is moderately sensitive to increases in emissions, while the U.S. Department of Energy/National Center for Atmospheric Research (U.S. DOE/NCAR) Parallel Climate Model (PCM) is less sensitive (see Hayhoe et al. 2004). Herbarium records and historic climate surfaces were used to derive niche models for plant distributions as functions of climate. These models were projected into future climate scenarios under two contrasting plant dispersal scenarios. For this paper, the results of the study were reanalyzed to obtain projections for the SFBA.

Under the most severe scenarios considered in the study, Loarie et al. (2008) estimated up to 53 percent of the California endemics currently found in the Bay Area are projected to disappear from the region. While the magnitude of species losses depends on emissions scenario and model sensitivity, the patterns of projected species losses were relatively consistent. Losses were projected to be more severe in California's interior than along the coast. This is due to greater warming in the interior of California and a larger disruption to the Mediterranean cool wet winters relative to warm dry summers. These projections, however, assume the persistence of the moderating influence of fog along the coast in future climate scenarios (see Section 2.1 above).

It is also important to consider species currently not present in the Bay Area that could move into this region as climate changes. Loarie et al. (2008) found that the Bay Area has the potential to serve as an important future climatic refuge for endemic plants currently found outside the region, provided they can keep pace with climate change. They estimated that under the most severe scenarios they considered (SRES A1FI and HadCM3), and assuming unlimited dispersal ability, one-third of California Floristic Province endemics found in the Bay Area by the end of the century would be climatic refugees from elsewhere in California. However, the models consistently projected that more endemic plants would be lost than gained. As a result endemic diversity would decrease in all scenarios, but particularly in those scenarios in which dispersal ability was limited. Likewise, the range sizes of endemic plants currently in the Bay Area are projected to decrease, on average. Under severe climate change scenarios, Loarie et al. (2008) projected that up to 66 percent of the California Floristic Province's endemic flora will experience severe reductions of more than 80 percent in range size. For the subset of endemic plants currently present in the Bay Area, up to 53 percent are projected to experience severe reductions in range size.

The studies of vegetation and plant species distributions summarized here are based entirely on correlative modeling of current distributions in relation to underlying climate maps. There remains a wide gap in understanding to link these modeling approaches to mechanistic or empirical studies based on physiological, behavioral, and demographic responses at the individual and population level. Experimental studies of grasslands (summarized below) have examined responses to multiple global change factors, and often found unexpected interactions and responses that demand novel explanations (e.g., Shaw et al. 2002; Suttle et al. 2007).

There is a critical need for the SFBA, and for California in general, to develop experimental and mechanistic studies coupled to large-scale modeling, both to test some of the predictions emerging from the models and to provide improved mechanistic understanding to refine model predictions. For example, current models do not incorporate direct effects of elevated CO_2 levels in the atmosphere, in part because there is no spatial variation in CO_2 concentrations that can be used to parameterize its effects. Elevated CO_2 is known to enhance water-use efficiency in many plants, as the higher external concentration of CO_2 allows plants to reduce stomatal conductance and reduce water loss, while maintaining photosynthesis and growth. Elevated CO_2 may also increase or decrease freezing tolerance in plants, depending on the species. In a study of *Yucca brevifolia* (Joshua Tree) in southern California, Dole et al. (2003) found that increases in freezing tolerance due to elevated CO_2, documented in experimental studies, could lead to an expansion of its future range; whereas, the effects of climate alone would lead to a decrease. Many more such studies are needed, as well as advances in modeling methods, to better integrate mechanistic and correlative approaches to project climate change impacts.

2.3 Wildfire and Vegetation Distributions

Current and future fire regimes will play a critical role in the distribution and dynamics of native plant and animal taxa in the face of changing climate. The disturbance created by fire could serve as a key trigger that facilitates climate-driven transitions among vegetation types, though fires may also allow for rapid colonization by invasive species. Impacts of climate change on fire regimes are complex, depending on interactions among primary productivity (i.e., fuel), vegetation types, and fire conditions (increased temperature and decreased relative humidity). For California as a whole, Lenihan et al. (2008) forecast modest increases in annual area burned, including increases in the SFBA, based on the fire module of the MC1 vegetation model. Westerling et al. (2009), modeling at a fairly coarse scale, forecast moderate declines in area burned over the coming century for the Bay Area under current vegetation distributions. However, if vegetation migrates in response to climate, moderate increases are forecast. Krawchuk and Moritz (2012; also see Parisien and Moritz 2009) have developed higher-resolution predictive models of fire regimes based on climatic factors, analogous to the methods used for species distribution modeling (Figure 4). Work is under way to generate high-resolution predictions for the Bay Area, and to couple fire and vegetation modeling, and these will be of great value for future conservation and development planning efforts.

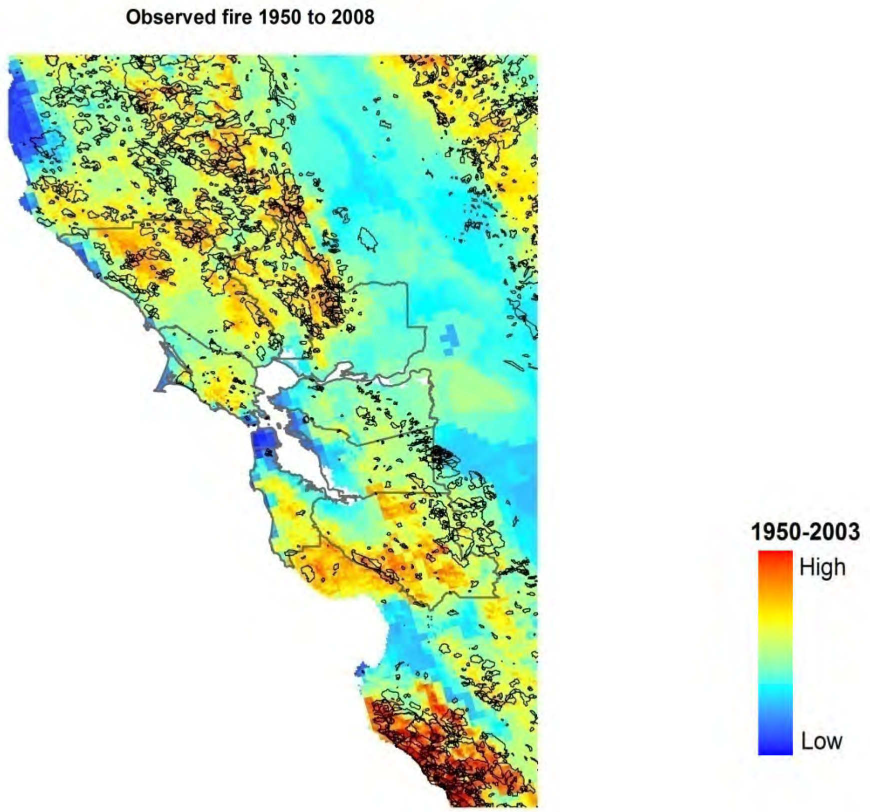


Figure 4. Observed Fire Perimeters from 1950 to 2008 in the Bay Area, and Modeled Probability of Fire Based on Underlying Climate Gradients (color legend)

Source: Courtesy of Meg Krawchuk and Max Moritz, UC Berkeley.

2.4 Invasive Plants

In this paper we have not analyzed or evaluated the role of invasive species under changing climates, or how climate change may favor or disfavor particular invasives. Modeling efforts to project climate change impacts on invasives are under way by the California Invasive Plant Council, to better inform management efforts to stop invasive plant spread.[3] Enhanced monitoring of invasives is also getting under way with the Bay Area Early Detection Network (Bay Area Early Detection Network 2011). Climate change is likely to favor the expansion of many invasive species. Invasives are by their nature species with a high capacity for rapid population growth and spatial range expansion. Disturbances, whether natural or anthropogenic, facilitate establishment and expansion of invasives by removing, at least temporarily, dominant native vegetation. The vegetation transitions modeled in response to climate change may be triggered locally by fire, disease, or severe drought or other abiotic stress. Any of these events, by removing existing vegetation, create opportunities for spread of invasives. Continued efforts to monitor and control the spread of invasive plants take on increased importance in the face of changing climates.

2.5 Terrestrial Animals

All animal species occupy a restricted range of characteristic habitats, so the projections discussed above for vegetation have wide-ranging implications for animals in any community. The habitat relationships of California wildlife provide the basis for modeling distributions of terrestrial vertebrates (Mayer and Laudenslayer 1988), and offer an important link between projected shifts in vegetation and their potential impacts on wildlife. In the SFBA, sea level rise and marsh inundation present threats to wetland animals (such as the endangered rail and sparrows mentioned above); decline of redwoods and other old-growth conifer forests threaten the region's marbled murrelets and spotted owls. However, few studies have examined potential climate change impacts on animal taxa in the SFBA.

Long-term studies of populations of the federally threatened Bay checkerspot butterfly (*Euphydryas editha bayensis*) at Stanford's Jasper Ridge Biological Preserve and other locations in the SFBA have served as a model for understanding effects of climate and topography on butterfly population dynamics. Checkerspot populations are very sensitive to the timing of larval emergence relative to the flowering time of their native food plants, and larval growth is also closely tied to thermal effects of topographic variation at very small spatial scales (Weiss et al. 1988; Weiss and Weiss 1998). Two of the Jasper Ridge study populations of Bay checkerspots went extinct in 1992 and 1998, and a demographic model strongly suggested that extinction was hastened by an increase in the variability in annual precipitation starting in the 1970s (McLaughlin et al. 2002). The later population to go extinct occupied a smaller area, but one with greater topographic heterogeneity, which buffered the impacts of precipitation by providing a greater range of microclimates. The increase in precipitation variability is consistent with projected effects of anthropogenic climate change, though it is not possible to attribute these individual extinction events to anthropogenic impacts at this point.

Forecasts of bird communities for the SFBA show a strong likelihood of species turnover through time as the climate changes (Stralberg et al. 2009). Many of the projected bird

---

[3] CalWeedMapper, http://calweedmapper.calflora.org/, California Invasive Plant Council

communities across the state have no current analog, suggesting species interactions and community dynamics will be difficult to predict based on current studies of extant communities. For the SFBA, projected species turnover (Bray-Curtis dissimilarity between present and future for each pixel) is strongly dependent on changes in precipitation under different GCMs (which serve as boundary conditions for the regional climate model used in this study). Species change is forecast to be greater using the Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 model, a warmer, drier future, compared to the NCAR Community Climate System Model (CCSM3.0), a warmer wetter future (Figure 3 in Stralberg et al. 2009). This is partially due to the forecast for Bay Area vegetation, as a much greater change from forest to shrubland is forecast when using the drier GCM.

We are not aware of any studies on potential climate change impacts on individual species or communities of terrestrial mammals in the Bay Area. The impacts of fragmentation on movement and connectivity among patches of core habitat have been addressed in several studies (Hilty et al. 2006; Merenlender et al. 2009). Currently, a Bay Area Wildlands Connectivity project is under way, and CalTrans/California Department of Fish and Game have recently completed the California Essential Habitat Connectivity Project, identifying important wildlife corridors connecting core wildland areas (Spencer et al. 2010). In the Bay Area, the linkages identified include the Inner Coast Range and the Gavilan Range, the Mt. Hamilton and Mt. Diablo Ranges, the Sonoma Mountains and Mayacamas Range, and others. Finer-scale work is also under way in the North Bay to prioritize corridors among large core areas of natural habitat (Merenlender et al. 2010), and to identify which corridors may provide the greatest advantage for future resilience of the lands network to expected climate change (A. Merenlender et al., unpubl.).

2.6 Velocity of Climate Change

The studies above highlight the importance of dispersal and migration as primary responses to changing climates, both at local and regional scales. The potential for species to move into the SFBA from outside, and to move among sites within the region, depends on whether species can keep pace with the speed with which particular climate conditions shift across the landscape. Spatial heterogeneity generated by topography and climate gradients is critical in this respect, and has been studied in detail for California and in recent studies of the SFBA.

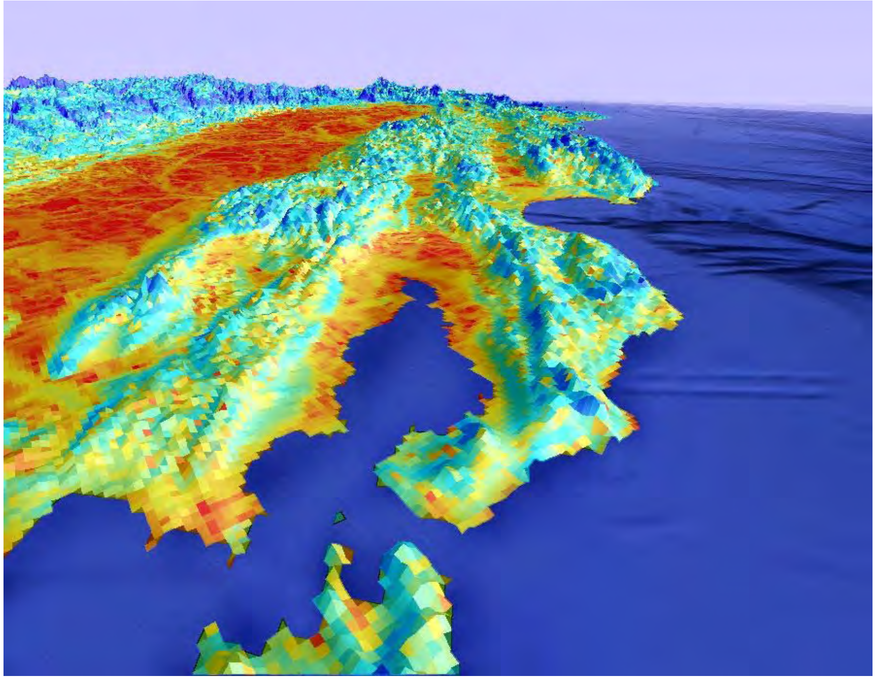


Figure 5. Velocity of Change for Mean Annual Temperature in the San Francisco Bay Area, Based on Ensemble Projections from 16 Climate Models for the A1b Emissions Scenario. Velocity of change is calculated as the rate of change per time divided by the spatial gradient of change, and ranges from approximately 0.01 km/yr (dark blue) to 5 km/yr (red).

Source: Redrawn from Loarie et al. 2009.

Loarie et al. (2009) estimated the velocity in kilometers per year (km yr^{-1}) for temperature isotherms moving across the landscape under future climate scenarios as the ratio of the rate of temperature increase (°C yr^{-1}) in the twenty-first century relative to the steepness of spatial gradients (°C km^{-1}) derived from historical climatologies. They found that under the moderate SRES A1B emission scenario, the global average speed of temperature movement in this century will be 0.42 km yr^{-1}. The edges of species ranges must therefore move at this rate to keep pace, if the species are closely tied and in equilibrium with temperature conditions. In the Bay Area, the velocity of temperature shifts is smaller (0.26 km yr^{-1}) due to relatively complex topography and steep climatic gradients along the coast (Figure 5). This result is consistent with lower speeds required in mountainous areas across the globe.

Loarie et al. (2009) also estimated the residence time during which present-day climates will persist within protected areas as the ratio of the linear dimension of protected areas (kilometers) to the velocity of climate change (kilometers per year). Only 8 percent of the world's protected areas are projected to exhibit overlap between current climates and end-of-century climates. This is due to relatively small sizes of most protected areas (on the order of one kilometer), high temporal gradients of climate change, and low spatial gradients. In the Bay Area, there are almost 500 contiguous protected areas of 100 hectares (ha) or more. Climatic heterogeneity, quantified based on the gradient of summer temperatures, is greater in large reserves, as expected, and also in reserves near the coast due to the steep coastal climate gradient (Ackerly et al. 2010). However, in a comparison of the current climate with an end-of-century projection based on the A1b scenario, only 8 of the protected areas have a sufficiently broad range of temperatures to maintain any overlap between the warmest sites in the present and the coolest sites in the future (Figure 6). In a similar analysis for all protected areas in California, only the largest reserves (>5000 ha), especially those spanning large elevational gradients of 1000 m or more, exhibit substantial overlap between historical and future climate, under A2 scenarios with rapid change (Ackerly 2012). Outside of protected areas, habitat fragmentation is expected to further decrease the ability for species to keep pace with climate change. Dispersal is expected to be even more limited for California's many edaphic (soil) endemics such as those found only on serpentine soils (e.g., *Streptanthus niger,* endemic to Marin County) or in vernal pools (e.g., *Limnanthes vinculans* and *Lasthenia burkei*, both endemic to Sonoma County).

It is critical to consider the role of spatial grain and fine-scale topographic effects in analyses of landscape heterogeneity. The results presented above are based on the 800 m PRISM climate surface, which captures the regional gradients of coastal-inland climate and overall elevational gradients of the Coast Ranges. At a finer scale, local topography (e.g., north versus south-facing slopes) affects solar radiation, surface temperature, and water balance, and cold-air drainages lead to local inversions of the elevational temperature gradient. The effect of cold-air drainages can increase the range of temperatures in a local landscape by ± 7°C–8°C (±13°F–14°F), relative to the values captured at the 800 m spatial scale (Van de Ven and Weiss, unpublished, cited in Ackerly et al. 2010). Recent advances in spatial downscaling of climate surfaces provide temperature and water deficit estimates at a 270 m scale (Flint and Flint 2012), and these data are currently being used for higher-resolution studies of climate change impacts for the California Energy Commission vulnerability analysis.

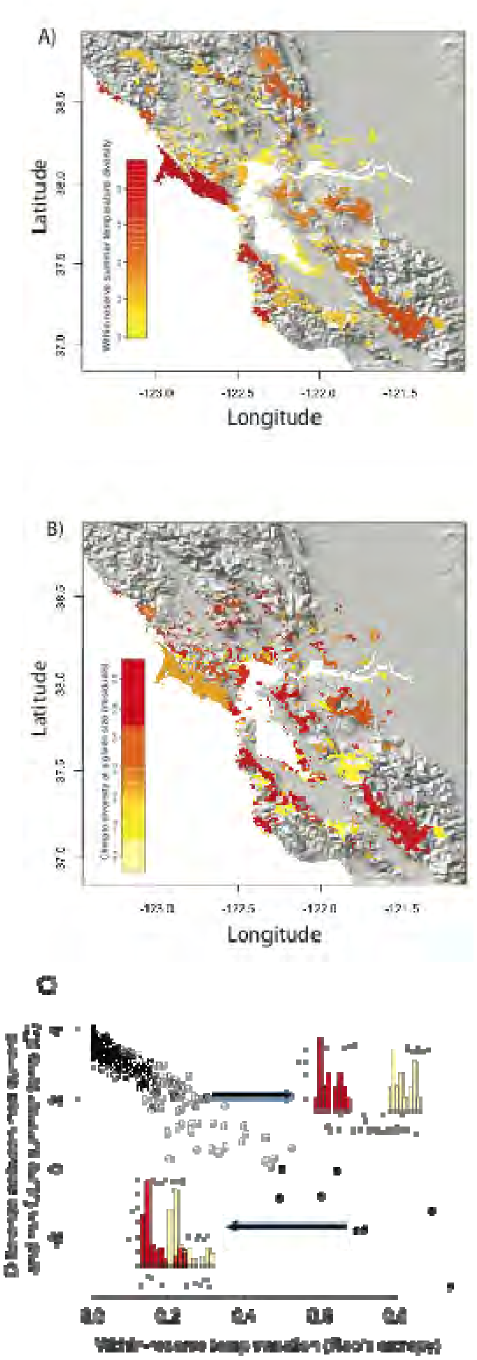


Figure 6. Variability of Summer Temperatures for Protected Areas of the San Francisco Bay Area. (a) Temperature heterogeneity across each reserve area, calculated as Rao's entropy, S, a measure of the spread of values across the range of temperatures. (b) Residual values of S after regression on reserve size. (c) Difference between the minimum summer temperature in the future observed across each reserve (A1b, warmer-drier scenario, 2070-2099) and the maximum temperature in the present, as a function of spatial heterogeneity in temperature. Positive values indicate no overlap between current and future temperatures across a reserve. Insets illustrate temperature distributions for two reserves.

Source: Reprinted with permission from Ackerly et al. 2010, Diversity and Distributions.

2.7 Interactions with Drought, Disease, and Herbivory

Other abiotic and biotic factors, such as disease, herbivory, drought, and extreme climate events, have important impacts on vegetation and biodiversity. The impacts of biotic factors may be enhanced under a changing climate, and the frequency and intensity of drought and extreme climatic events is forecast to increase.

In the SFBA, sudden oak death (SOD, caused by the introduced pathogen *Phytophthora ramorum*) has spread rapidly in the past ten years, and caused widespread mortality of sensitive tree species, especially tanoak (*Notholithocarpus densifolorus*). In redwood forests, the dying tanoak may be replaced by redwood regeneration, reducing the species and structural diversity of the forests (Ramage and O'Hara 2010). In the short term, the increased fuel load from dead tanoak and other species may increase fire intensity and spread, and this could exacerbate climate change impacts on fire in coming decades. Sudden oak death spread and distribution are influenced in part by climate (e.g., Meentemeyer et al. 2004), so climate change may precipitate further disease spread.

In recent years, major episodes of tree mortality associated with drought and/or heat stress have now been observed on every continent (Allen et al. 2010). The best known in the western United States are the deaths of pinyon pines in Arizona and New Mexico, and bark beetle outbreaks in Rocky Mountain pine forests. Causes of death, from the proximate level for individual trees, as well as a broader ecological perspective, are not always straightforward. Drought stress, and reductions in carbon stores, make trees more susceptible to outbreaks of herbivores and disease (McDowell et al. 2008). Dead trees also create elevated fire risks. In California, projected changes in precipitation vary widely; however, models of soil water deficit suggest that dry season water availability will decline due to increased evapotranspiration in a warmer world, even if precipitation increases (see Micheli et al. 2010). Potential impacts on woody plants of the SFBA are unknown at this point.

2.8 Estuarine and Intertidal Habitats

Following European settlement in the San Francisco Bay Area, land use conversion primarily for agriculture and urbanization resulted in a 90 percent reduction of wetlands in the estuary (San Francisco Estuary Project 1991). Levee construction during the twentieth century resulted in the additional loss of wetlands, with an estimated 4-8 percent of original wetland area remaining (Atwater and Hedel 1976) prior to the implementation of restoration activities during the last several decades. Restoration activities have successfully restored approximately 8,281 ha, or 3.8 percent of the original wetland area, with an additional 5,854 and 10,869 ha of restoration projects currently in process or planned, respectively (see www.californiawetlands.net/). The remaining tidal marsh habitat in the estuary represents the largest extent of tidal marsh in the western United States and provides habitat for federally listed species such as the salt marsh harvest mouse (*Reithrodontomys raviventris raviventris*), California clapper rail (*Rallus longirostris*) and California black rail (*Laterallus jamaicensis)*. Additionally, invertebrates present in intertidal mudflats provide important foraging resources for shorebirds and the estuary serves as a critical stopover for migratory waterfowl on the Pacific Flyway. Sea-level rise could influence the quality, quantity, and accessibility of avian foraging resources within the estuary resulting in a change in carrying capacity of the system.

Tidal marshes within the San Francisco Bay Estuary are extremely sensitive to sea level rise, with marshes either eroding or accreting depending on the frequency and duration of inundation, the amount of suspended sediments available, and the accumulation of organic material from vegetation. Recent modeling has shown that tidal marshes in the estuary could be maintained in the San Francisco Bay if there is an adequate supply of sediments, even under high rates of sea level rise (Stralberg et al. 2011). However, recent studies document a sharp decline in suspended sediment concentrations in the Bay over the past two decades (Schoellhamer 2011), and if these trends continue high- and mid-marsh habitat could decrease by over 90 percent under high rates of sea level rise over the next century.

The projected decline in high- and mid-marsh habitat may have important consequences for tidal marsh biodiversity. The high-marsh zone is rich in plant species, relative to mid- and low-marsh, and hosts several endangered plant species, including salty bird's-beak (*Chloropyron molle subsp. molle*). The California state-listed black rail and the federally endangered clapper rail are both associated with high-marsh vegetation (Conway and Sulzman 2007; Stralberg et al. 2010). Both species use the high-marsh habitat for refuge; black rails face lower predation rates in areas containing high-marsh habitat, and the black rail and clapper rail use high-marsh habitat to escape high tides (Shellhammer 1989; Foin et al. 1997). Three endemic subspecies of tidal marsh song sparrow (*Melospiza melodia*) (Chan and Spautz 2008; Spautz and Nur 2008a; Spautz and Nur 2008b) and the endemic salt marsh yellowthroat (*Geothlypis trichas sinuosa*) (Gardali and Evens 2008) all primarily use mid-marsh habitat for breeding, as it contains the majority of vegetation within the tidal marsh. These species are projected to experience population declines under most scenarios with high rates of sea level rise (Veloz et al. 2011) where high- and mid-marsh habitat are also projected to decline (Stralberg et al. 2011).

2.9 Coast and Nearshore Habitats

Physical changes to coast and nearshore marine environments include sea level rise, coastal erosion and flooding, changes in precipitation, land runoff, ocean-atmosphere circulation, and ocean water properties. These changes in turn will lead to biotic responses within ocean ecosystems, including changes in physiology, phenology, and population connectivity, as well as species range shifts. These changes were outlined in the *Climate Change Impacts Report* (Largier et al. 2010) that identifies and synthesizes potential climate change impacts to habitats and biological communities along the north-central California coast, and the main points from the Executive Summary are included here. More detailed discussion of marine habitats, and of the San Francisco Bay estuary, is beyond the scope of this paper (see, for example, Cloern et al. 2011).

Sea level rise will exacerbate coastal flooding, shoreline erosion, saltwater intrusion into groundwater aquifers, and inundation of wetlands and estuaries, as well as threaten cultural and historic resources and infrastructure. Coastal erosion will increase as a result of rising sea level, intense precipitation and runoff, and increased extreme wave and storm conditions. Coastal habitats will be affected directly by habitat loss through erosion, or indirectly via human responses such as coastal armoring (e.g., construction of sea walls), beach nourishment (importing sand), or planned retreat (moving infrastructure inland from the coast). Changes in runoff will lead to increased flooding of coastal lowlands, erosion of estuarine habitats, increased delivery of watershed material to the ocean, expanded plume areas of freshwater -

ocean mixing, and increased near shore stratification of the water column, which can lead to lower biological productivity in nearshore waters.

Surface ocean temperatures have increased offshore of the north-central California continental shelf. This increase in temperature has significant effects on water column structure (i.e., stratification), sea level rise, and ocean circulation patterns. Continental shelf waters over the same region have cooled over the last 30 years (by as much as 1°C [1.8°F] in some locations) due to stronger and/or more persistent upwelling during spring, summer, and fall. The strength and variability of upwelling winds affect the amount of primary production available, and the amount delivered to coastal ecosystems rather than offshore ecosystems. Natural climate fluctuations in association with El Niño and other Pacific Basin-scale phenomena will lead to more extreme conditions. The increased concentration of CO_2 in the ocean will lead to ocean acidification and will result in decreased shell growth in key invertebrate species.

Physical changes influence a variety of critical biotic processes, such as metabolic rates, planktonic transport, prey availability, and/or predation rates. The response of a single species to climate change depends not only on environmental changes, but also upon how other interacting species will respond to this change. A northward range expansion of organisms is anticipated, owing to warming of ocean waters, although non-uniform changes in ocean temperature at multiple spatial scales will complicate expectations. Changes in the timing of the spring transition or the seasonal peak in upwelling could have significant population-level impacts for many species. The availability of prey species for fish, seabirds, and marine mammals may be negatively affected by changes in upwelling and ocean acidification.

Productivity in open-ocean pelagic habitats is controlled through a delicate balance between wind-driven upwelling and stratification of the water column due to surface warming. Increasing surface temperatures will reduce vertical mixing and cause shifts in the phytoplankton community. In near-shore habitats, organisms are susceptible to ocean acidification, changes in upwelling and water stratification that affect nutrient delivery, increases in wave heights that affect sediment redistribution, and sea level rise that decreases light availability to macroalgae. In rocky intertidal habitats in particular, increases in average water and air temperature and the occurrence of extreme conditions can result in mass mortality of intertidal organisms.

Estuary habitats along the coastline may be most affected by changes in the timing and persistence of seasonal mouth closure and the intensity and timing of seasonal runoff, as well as the continued rise in sea level. Sediment delivery and availability will strongly influence the ability of estuaries to adjust to rising sea level and maintain intertidal estuarine habitat. Impacts on the San Francisco Bay estuary will depend on interactions of water management and climate on freshwater flows and sediment loads from the Delta, together with rising sea levels entering at the Golden Gate, and a long and heavily developed shoreline.

Multiple stressors may interact to produce unexpectedly severe impacts on biodiversity and ecosystem health. Additional stressors within the region include pollution, invasive species, fishing, disease, habitat modification, wildlife disturbance, and development of infrastructure along the coast and at sea.

Section 3: Climate Change Impacts on Ecosystem Services

Ecosystem services are natural environmental processes that supply benefits to society (United Nations Environment Programme 2005). Emerging awareness of the importance of ecosystem services has stimulated considerable research focusing on economic valuation, social capacity, and scientific characterization of ecosystem services in recent years (Vihervaara et al. 2010). Climate change impacts are thought to affect the supply and distribution of benefits from some ecosystem services (Schroter et al. 2005). Uncertainties associated with future climate scenarios pose challenges in planning for biodiversity conservation and predicting impacts of changes to ecosystem services on society (Balmford and Bond 2005).

This section focuses on five ecosystem services that are important to the SFBA: **carbon storage, forage production, water supply and quality**, **pollination,** and **outdoor recreation**. We review existing peer-reviewed literature to provide an assessment of the state of knowledge on the biophysical attributes of (and the potential impacts of climate change on) each service in this spatially defined region. We focus our discussion here on services provided by terrestrial ecosystems. A recent analysis provides an economic valuation of ecosystem services linked to San Francisco Bay, including fishing, shipping, recreation, and scenic amenities (Battelle Memorial Institute 2008). In discussions of ecosystem services in particular, future analyses should examine the region as a whole, integrating the services supported by terrestrial, freshwater, estuarine, and marine ecosystems.

3.1 Carbon Storage in Soils and Vegetation

Soils and vegetation are important global reservoirs of carbon, storing approximately 2000 and 710 gigatons (Gt) of carbon (C), respectively (Janzen 2004). Locally, these reservoirs are an important component of California's strategy for achieving the statewide goal of reducing greenhouse gas emissions through C sequestration. Terrestrial C sequestration is defined as the net removal of CO_2 from the atmosphere into long-lived stocks of carbon, including aboveground biomass, belowground biomass, or organic and inorganic C in soils. Net sequestration can be achieved through increased C inputs into ecosystems, decreased outputs, and/or increasing the turnover times in C stocks.

While highly urbanized, the SFBA consists of diverse ecosystems, including coastal redwood forests, oak savannahs, and agricultural croplands, as described above. Agriculturally, the region is home to specialized crops, organic production, locally important farmland, vineyards, and market-niche range products (Hart 2003; Huntsinger et al. 2010). Farmland (not including urban farms) occurs on 591,167 acres (or 13 percent of the Bay Area total land area; California Dept. of Conservation 2009). Half of agricultural land use area in the Bay Area is considered unique or locally important. Grazing land use occurs on 1,745,237 acres (or 40 percent of the Bay Area total land area; California Dept. of Conservation 2009). There is potential for these managed systems to gain more C through grazing management, pasture improvement, no-till agriculture, and conversion to perennial crops (Conant et al. 2001; Kroodsma and Field 2006). Freshwater and tidal wetlands are also critically important in terms of carbon sequestration and could play a role in greenhouse gas emissions mitigation in California (see Trulio et al. 2007).

The SFBA, especially Marin, Sonoma, and Santa Cruz Counties, is also home to substantial redwood forest ecosystems (Figure 3). The amount of C stored as aboveground woody biomass, root biomass, and soil organic C in coastal redwood ecosystems is currently unknown, though quantification efforts are under way. Some estimates suggest that living aboveground biomass in coastal redwoods contains five times more C than any other forest on the planet (Sillett et al. 2010; Sillett, unpublished). There are few data, however, about redwood's capacity for storing C belowground. Recently it has been shown that fine roots of old-growth redwood stands and their associated soil C stocks are similar to other vegetation types (McFarlane et al. 2010). This suggests that the vast majority of the C sequestered belowground by coast redwoods resides in coarse root biomass. This question merits further research.

Terrestrial ecosystems in the SFBA could sequester a significant amount of C by increasing the amount of C stored in soil and vegetation through management. For example, the Marin Carbon Project is focusing its efforts on identifying opportunities to increase C storage in rangelands in Bay Area. However, the quantity stored is highly dependent on future changes to temperature and precipitation. Carbon source-sink relationships in Mediterranean climates are driven largely by patterns in the timing and quantity of precipitation. Precipitation changes are more uncertain than temperature changes in most climate models. Shaw et al. (2009) assessed future changes in C storage in living trees in California using different climate models in combination with future greenhouse gas emissions scenarios. Using the warmer, wetter climate model (PCM 1), tree biomass across the state decreased by 9 percent by the end of the century relative to the business-as-usual baseline scenario. In contrast, the hotter, drier climate models (GFDL and CCSM 3) resulted in a 26 percent decrease by the end of the century relative to the baseline. Additionally, the amount of aboveground biomass C consumed by fires is projected to rise in all combinations of climate change and emissions scenarios. Thus, climate change may lead to a decline in the natural ability of forests in the SFBA to store carbon.

Coastal redwoods are buffered by fog water contributions from summer drought characteristic of the Bay Area's Mediterranean climate. Although total fog water inputs are small, they are important for ecosystem functions by providing water and nutrients in water-limiting times, thereby supporting redwood growth and maintenance (Oberlander 1956; Weathers 1995). A study of redwood forests in Sonoma County found evidence of greater production with increasing fog water contributions (Ewing et al. 2009). As previously mentioned, fog frequency has declined 33 percent since the early twentieth century, leading to increasing summer drought stress (Johnstone and Dawson 2010). Long-term reductions in fog are expected to decrease C storage in redwoods and other coastal endemic species (Biondi et al. 1997; Williams et al. 2008).

Annual grassland ecosystems provide important opportunities for experimental studies of global change, though their productivity and carbon storage potential is low at a landscape scale. The Jasper Ridge Biological Preserve at Stanford University has been the site of a long-term study of multifactorial effects of temperature, nutrients, precipitation, and elevated CO_2. The direct and interactive effects of elevated CO_2 are of particular interest, as these can only be addressed using experimental approaches. Initial experiments found that elevated CO_2 leads to reduced stomatal conductance and higher water use efficiency of the annual grasses, which can increase soil moisture and favor late-season annuals and perennial forbs (Chiariello and Field 1996). In the first several years of the multi-factorial experiment, elevated CO_2 also suppressed the stimulation of productivity by the other factors (Shaw et al. 2002), though these effects diminished in subsequent years (Dukes et al. 2005). This and other global change experiments repeatedly point to the complexity of interactions among environmental factors and different species within the communities, and caution against simple forecasts of community and ecosystem level responses (Zavaleta et al. 2003; Suttle et al. 2007).

3.2 Forage Production

Forage production in grasslands and oak savannahs plays a vital role in the livestock industry in California (see accompanying paper by Chaplin-Kramer 2012). Thirty-four million of the state's 57 million acres of rangeland are grazed (Stewart et al. 2003). Production of forage for grazing is economically important in the SFBA as well. A majority of the 40 percent of land in the SFBA that is used for grazing is privately held (Figure 2 in California Dept. of Conservation 2009). The Bay Area is home to traditional and niche ranching markets that depend on high quality and quantity of forage production (e.g., Strauss Family Creamery, Clover Organic Farms, Marin Sun Farms, Clark Summit Farms, Gospel Flat Farm). The area of rangeland in the Bay Area has been steadily declining at an average rate of 4,716 acres lost per year since 1984, primarily due to land use conversion to urban and other build environments (California Dept. of Conservation 2009; Huntsinger et al. 2010).

Rangelands provide additional services beyond being a source of forage for grazing that are not explicitly considered in this paper. For example, rangelands may buffer urban growth, preserve open spaces at a low cost, and diminish fire hazards to adjacent suburban areas (Stewart et al. 2003). Rangelands also provide a number of cultural and lifestyle amenities to land owners and the public, such as natural beauty, recreation, and rural lifestyle benefits (Huntsinger et al. 2010). Additionally, rangelands are linked to biodiversity through grazing management, which can reduce diversity of invasive species (Stohlgren et al. 1999; Marty 2005), and maintain or increase grass and forb species richness (Collins et al. 1998; Hayes and Holl 2003; Kohyani et al. 2008).

Non-native annual grasses and forbs dominate forage vegetation in the SFBA. Productivity of forage is highly spatially and temporally variable, and can be explained largely by a combination of site-specific conditions and precipitation patterns. Forage production tends to increase with increasing precipitation in annual grasslands, similar to perennial grasslands (Sala et al. 1988; McCulley et al. 2005; Chou et al. 2008). The magnitude of forage produced in an annual grassland or oak savannah in a given year is extremely sensitive to timing and magnitude of rainfall and the previous year's production (Hedrick 1948; Heady 1956; Heady 1965; Bartolome et al. 1980; Chou et al. 2008).

Climate change impacts, particularly shifting precipitation regimes, are expected to affect the long-term trends in forage production, plant community composition, and wildfire impacts. However, the extent to which climate change will alter forage production and the associated impacts on the rangeland economy in the SFBA is uncertain. At the statewide level, Shaw et al. (2009) modeled a 14 to 58 percent decline in forage production, resulting in a decline of cattle ranching profits by $22 to $92 million per year. An analysis by the California Forest and Rangeland Assessment (Caluza et al. 2010) found that rangelands in the SFBA bioregion face significant threat from wildfires. Climate change may exacerbate loss of forage due to wildfires.

The ability of a rancher to adapt to the risks of climate change depends on available financial resources, flexibility of management approaches, and on the predictability of changes in forage production or extreme climatic conditions like drought. Decreases in forage production in the short-term may lead to an increase in the cost of ranching due to rising needs for supplemental feed and due to increased opportunity costs from unpredictability of stocking levels. In the long-term, decreased forage production may make rangeland management economically and ecologically unsustainable or significantly change the type of end products from rangeland systems.

3.3 Water Supply and Quality, and Flood Control

The hydrologic cycle is a multifaceted ecosystem service that plays critical roles in the physical, chemical, and biological processes of the Earth. Ecosystems control the characteristics of freshwater resources by regulating the partitioning of precipitation into evaporative, recharge, and runoff processes (Vorosmarty et al. 2005). The capacity of ecosystems to sustain an adequate quantity and quality of freshwater is a service invaluable to nutrient dynamics, human well-being, and many threatened and endangered species. See accompanying paper by Sicke et al. (2012) for additional analysis of climate change impacts on water supplies in the SFBA.

Water quality is strongly influenced by landform and land use at multiple spatial and temporal scales (Allan 2004). Land use activities can degrade water quality, destroy wetland and riparian habitat, and alter species composition and diversity (Lotze et al. 2006). The effects of human impacts on aquatic ecosystem services may deepen with climate change, particularly due to predicted consequences of climate change on terrestrial ecosystems, such as shifts in riparian and wetland vegetation and changes to the hydrologic cycle (Meyer et al. 1999). Thus, catchment-wide approaches to protecting watershed landscapes are important for maintaining or restoring aquatic ecosystem services (Richards et al. 1996). For example, preservation of agricultural lands under "best management practices" is correlated to high levels of stream macroinvertebrate diversity, indicating high levels of water quality (Moore and Palmer 2005).

The SFBA is a model for catchment-scale approaches to protecting water resources through land preservation and conservation. Some of the largest open space reserves in the region were set aside explicitly for watershed protection, including San Francisco Watershed Lands (> 8000 ha), the Marin Municipal District Watershed (7300 ha), and the Los Vaqueros Watershed (6500 ha). In the case of Marin County, the reliance on a local, but limited, water supply played a critical role in political decisions to limit development, making the county an early leader in open space preservation (Griffin 1998). Some watersheds, such as the San Francisco Watershed Lands around the Crystal Springs, Calaveras, and San Antonio reservoirs, are closed to recreational use, which almost certainly enhances their role in biodiversity conservation. Many other organizations participate in watershed land preservation, including land trusts, irrigation districts, county conservation districts, farm and agricultural bureaus. Programs (e.g., Integrated Hardwood Range Management Program) provide outreach and education to land owners regarding the best management practices to maintain or enhance water quality. However, assessing the contribution of particular parcels or conservation strategies to water quality and other ecosystem services is difficult, due to the variability in the properties, organizations, and institutions involved (Merenlender et al. 2004).

Tidal marshes in the SFBA provide a suite of important local ecosystem services, including flood control, runoff filtration, mitigating heat extremes, carbon sequestration, healthy fisheries, and outdoor recreation opportunities. A major climate change threat to tidal marsh ecosystems is sea level rise (see above). The future extent and type of tidal marsh habitat is highly dependent on the relative rates of sea level rise and suspended sediment concentrations. Regions with high suspended sediment concentrations, such as marshes in the Petaluma River and South Bay, may be more resilient to sea level rise; whereas, other tidal marsh habitat may have insufficient sediment supply to keep pace with sea level rise. Efforts are under way to model climate change impacts on SFBA tidal marsh habitat (Stralberg et al. 2011).

Infrastructure delivers water to the water districts in the SFBA sourced from the Sacramento-San Joaquin Bay Delta (Delta), its major tributaries (the Sacramento, San Joaquin, and Mokelumne Rivers), the Hetch Hetchy Reservoir, and the Russian River (to Sonoma County). More than half of Californians rely on water from the Delta to some extent. The Delta supplies an estimated 100 to 160 gallons per person per day to the Bay Area (Salah-Mars and McCann 2008). Approximately 35 percent of the 33 million acre-feet of water that pass through the Delta annually is consumed (Isenberg et al. 2008). Key consumptive uses of water provided by the Delta are for drinking, domestic use, and agriculture. Water is confined to 10 percent of the total area by a series of vulnerable 100-year-old levees. These water supply services are maintained by preventing and limiting the degradation of water quality from agriculture and urban ecosystems, regulating the supply of water for consumptive uses, and by maintaining and restoring the region’s freshwater and estuarine wetlands. Briefly, climate change will shift the distribution and flows of supply services as water becomes generally less available. As Delta water becomes more saline due to sea level rise, importing water to agricultural areas in the SFBA becomes more expensive. Water recycling and desalination have the potential to ameliorate climate change impacts on water supply to the SFBA.

In addition to these consumptive uses, water in the Delta also provides habitat for biodiversity, outdoor recreation services, and agricultural production. Of the 837,594 acres of land in the Delta, 557,896 acres (66 percent) are used for agricultural production (Isenberg et al. 2008). The Delta also provides habitat to 500 species of fish and wildlife; 105 of these species are designated by state and federal agencies as threatened or endangered (California Department of Water Resources 2009). The accompanying paper by Moyle et al. (2012) addresses impacts of climate change on freshwater fishes.

The provision of water from the Delta faces a number of serious threats, such as encroaching urbanization, seismic activity, flooding, and invasive species. Climate change is also identified as a major direct driver of the changes to the provision of freshwater resources (Nelson 2005). Climate change-induced periods of drought or longer dry seasons in the region will exacerbate problems in meeting demand for water by reducing the supply of water from precipitation (Stewart et al. 2003). The ultimate source of water in the Delta is from the Sierra Nevada snowpack, which is predicted to decrease substantially (Wallis et al. 2008). Climate change may also increase the risk of flooding, levee failure, and infrastructure damage in the Delta. These impacts may be a result of altered river flows on daily and seasonal timescales, rising sea level, changes in wind speeds, and accelerated subsidence (Salah-Mars and McCann 2008).

The Delta and other SFBA wetlands also buffer urban areas from flooding, but these areas are vulnerable to climate change. In a statewide analysis, Heberger et al. (2009) estimate that only 55 percent of surrounding habitat would be viable for wetland migration to survive a 1.4 m (4.6 ft) rise in sea level. They also estimate that this projected sea level rise would put approximately $100 billion worth of assets at risk, about two-thirds of which are concentrated in the SFBA (Heberger et al. 2011).

Sea level has risen nearly 20 cm over the past century. Climate models project an average increase of sea level by 100 to 140 cm by the end of the century, risking flooding and inundation of salt water into the estuarine system, but projections range from 10 to 200 cm (Cayan et al. 2006; Pfeffer et al. 2008; Cayan et al. 2009; Heberger et al. 2009). The frequency of extreme sea levels events is projected to occur as a result of episodic events superimposed on higher baseline sea level and potentially more frequent or severe winter storms (Cayan et al. 2008). The United States Geological Survey projects that a 1 m rise in sea level will inundate an additional 209,920 acres of the Delta (Isenberg et al. 2008). In addition to posing a threat to the quality and supply of water from the Delta, sea level rise also threatens coastal populations. In the Bay Area, 110,00 residents of San Mateo county and 66,000 residents of Alameda County are most at risk. Infrastructure, including the San Francisco and Oakland airports, wastewater treatment plants, and hazardous waste treatment plants are at risk of coastal flooding in the Bay Area. Some of the most serious impacts may result from extreme sea level rise events associated with high tides, storm surges, and freshwater floods from headwaters in combination with sea level rise (Cayan et al. 2008).

3.4 Pollination Services

Bees and other pollinators in natural ecosystems provide a critical service to local food producers and to native flora in the SFBA. Though highly urbanized, the SFBA is considered an insect biodiversity hotspot (Connor et al. 2002). Pollination by native, unmanaged bee populations enhances production of a number of crops in California, including watermelon (Kremen et al. 2004) and tomatoes (Greenleaf and Kremen 2006). Organic agriculture in the SFBA relies in part on native bees and other non-colony forming insect pollinators for crop production. The capacity for pollinators to provide this service depends largely on plant/pollinator interactions, which can be altered spatially by landscape patchiness and temporally by phenological changes (Memmott et al. 2007).

In general, scientific understanding of the effects of climate change on mutualistic plant-pollinator interactions is limited (Visser and Both 2005), as empirical research in this area is sparse (Kremen et al. 2007). One major pathway for climate change to affect pollination services is by altering the phenology of both plants and pollinators. Global observations indicate that many plant species have responded to increasing temperatures and changes to other environmental cues (e.g., precipitation, snowmelt, soil humidity) by flowering earlier in the last 20 to 50 years (Fitter and Fitter 2002); insect-pollinated plants generally react more strongly to increased warming than do wind-pollinated plants (Miller-Rushing et al. 2007). Likewise, the date of first emergence of butterflies, bees, and other insect pollinators is strongly correlated with temperature and topographic effects on energy balance (Gordo and Sanz 2006, Weiss and Weiss 1998, Weiss et al. 1988). Future phenological responses of plants and pollinators to climate change may be nonlinear, and depend on the interaction of temperature and other environmental cues. Depending on these interactions, changes in plant and pollinator phenology due to climate change may act in concert or vary across species (Hegland et al. 2009).

It is, so far, unclear how climate change will impact pollinators native to this area, and how that disruption will affect agricultural production in the SFBA. Managed bees in the United States are at risk of Colony Collapse Disorder (CCD), a phenomenon observed since 2006 and defined by large-scale unexplained losses of managed honey bees (*Apis mellifera*). Descriptive epidemiological case studies indicate that CCD is contagious or caused by exposure to common risks factors, but cannot be explained by a single causal agent. Colony Collapse Disorder is thought to have multiple causes and may involve an interaction between several stress factors. There is no evidence yet of climate change playing a direct or strongly indirect role in the cause or spread of CCD.

3.5 Outdoor Recreation and Quality of Life

Outdoor recreation is a critical cultural service provided by natural and semi-natural landscapes in the SFBA. In the SFBA, large metropolitan areas are intermixed and surrounded by an abundance of undeveloped land. These breathtaking landscapes, diverse vegetation and wildlife communities, and easy access supply a constant flow of outdoor recreational activities, such as hiking, biking, wildlife viewing, camping, and water sports, for local residents and visitors alike. Although difficult to quantify in economic terms, quality of life benefits generated from access to outdoor recreation in the SFBA represent an important ecosystem service. Direct and indirect economic benefits include jobs in the outdoor recreation sector and indirect benefits to local communities. Outdoor recreation in California contributes approximately $46 billion annually to the state's economy and supports 408,000 jobs (Outdoor Industry Foundation 2006). Indirect and induced economic impacts on local communities lead to $28.1 billion annually in retail sales and services statewide (Outdoor Industry Foundation 2006). Regional, state, and national parks in the SFBA provide a direct economic benefit by generating state revenue and creating jobs. Secondary economic impacts of outdoor recreation services included indirect and induced business activities associated with recreation tourism.

Napa Valley vineyards attract 4.7 million visitors annually, of which 53.6 percent are from the Bay Area (Cai and Ismail 2006). The total economic impact from this industry is about $1.3 billion per year, supporting $500 million in local wages and salaries. Thus, potential climate change impacts to wine grapes and vineyard management are economically important. Wine grapes are highly sensitive to temperature and other climate conditions, and phenological data from 1937 to the present have been used as an indicator of temperature in climate change research (Chuine et al. 2004; Rosenzweig et al. 2007). Observed increases in nighttime and spring temperatures in the latter half of the twentieth century along coastal California led to higher-quality wines and larger grape yields in the Napa and Sonoma valleys. An average annual temperature increase of 1.13°C (2.0°F) has resulted in an advanced start to the growing season by 18-24 days in the region (Nemani et al. 2001). Earlier and unhindered phenological events (bud break, flowering, fruit set, veraison, harvest, and leaf fall) due to warmer spring temperatures are likely to increase yields and produce higher-quality harvests (Nemani et al. 2001). A recent review of climate change impacts to grape quality highlights potential challenges, such as increased sugar concentrations, lower acidities, and modified aroma compounds (de Orduña 2010).

In addition to the economic benefits of recreation services provided by natural and semi-natural environments in SFBA, open spaces supply quality-of-life benefits to the region's residents. The availability of outdoor activities and viewsheds attract businesses and enhance local communities. Environmental degradation to public lands in SFBA damages the economically significant recreation services and the quality-of-life benefits to local residents. Potential risks from climate change to outdoor recreational activities include altered vegetation or animal communities, changes in water availability, and extreme climatic events.

Section 4: Conservation Strategies and Climate Adaptation

Research and implementation of conservation strategies that could reduce climate change impacts on biodiversity are receiving considerable attention in California and worldwide. The Biodiversity and Habitat chapter of the California Climate Adaptation Strategy (California Natural Resources Agency 2009) emphasizes the importance of creating a large-scale and connected network of protected areas, restoring and enhancing ecosystem function in the face of changing conditions, and re-evaluation and adjustment of management priorities and strategies to incorporate climate change. Here, we briefly address current work in the SFBA, especially in strategic planning of open space preservation, as well as general challenges facing restoration ecology and management of wild plants and animals. Our aim is primarily to review existing resources and highlight key issues, not to advocate or rigorously evaluate specific adaptation strategies.

4.1 Open Space Preservation

The network of open space preserves together with the matrix of working landscapes across the Bay Area provides the foundation for the conservation of biodiversity and enhanced ecosystem services in the face of twenty-first century climate change. Over the past four years, the Bay Area Open Space Council has developed the Upland Habitat Goals Project, a long-term strategic plan for open space acquisition in the Bay Area (Bay Area Open Space Council 2011). Upland Habitat Goals divides the SFBA into 34 ecoregions mapped around major watersheds and mountain ranges, and uses the framework of coarse-filter and fine-filter conservation targets to prioritize regions for future conservation that will span the full range of vegetation types across the region, as well as species and habitats of special concern. Using the software program Marxan, a boundary-length minimization algorithm was used to identify contiguous areas, building on the current network. The resulting Conservation Lands Network (CLN) identifies acquisition priorities across the region, particularly in the Peninsula Coast Ranges, the Sonoma Mountains, the Berryessa-Mount Saint Helena region, and around Mount Hamilton (Bay Area Open Space Council 2011). This regional analysis parallels efforts to develop a statewide system of large marine and terrestrial reserves spanning all major ecological regions (California Natural Resources Agency 2009). The California Department of Fish and Game, through its newly created Climate Science and Renewable Energy Branch, is playing an important leadership role in the development and implementation of adaptation strategies, and coordination among government agencies and stakeholder groups (see CADFG 2011).

Chan et al. (2006) mapped several ecosystem services for the central California coast, including most of the Bay Area, in a preliminary effort to incorporate ecosystem services into a systematic conservation-planning analysis (Figure 7). They found that a conservation plan to maximize biodiversity conservation captured some of the same areas that would be prioritized for carbon storage, flood control, outdoor recreation, and water provision. However, the distribution of biodiversity was negatively correlated with areas of forage production and pollination services. This approach is valuable to identify both synergistic and conflicting priorities in open space conservation, depending on a range of alternative conservation targets. Further applications will require higher resolution mapping of ecosystem services, which presents many challenges, and this is a topic that merits greatly increased attention.

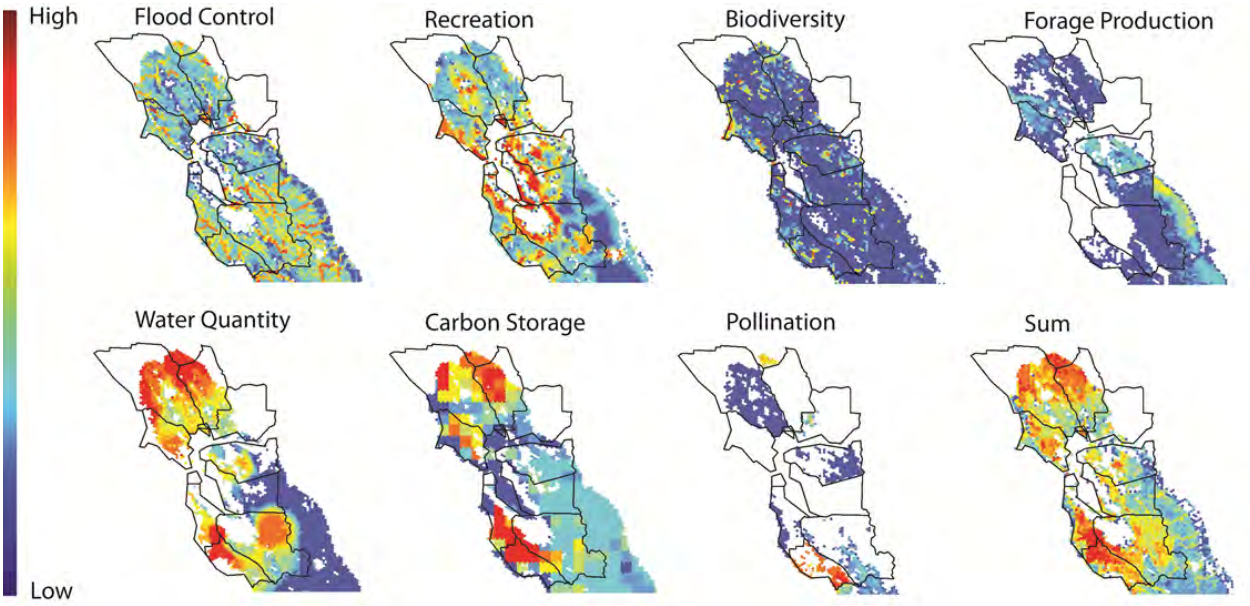


Figure 7. Preliminary Mapping of the Relative Value of Ecosystem Services in the San Francisco Bay Area

Source: Redrawn from Chan et al. 2006, PLoS Biology.

Current work, under way in 2010 and sponsored in part by the California Energy Commission vulnerability analysis, is examining how climate change impacts can be incorporated into open space acquisition priorities. One of the core concepts guiding this work is the importance of spatial heterogeneity for resilience of native communities in the face of climate change (Ackerly et al. 2010). Heterogeneous landscapes provide two related, but distinct, benefits. First, as discussed above, climate change is expected to cause shifts in the distributions of species and major vegetation types. In landscapes with steep climate gradients, the projected range shifts occur over shorter distances, and are more likely to be within the dispersal range of the existing plants and animals, especially over decadal to century time scales. Second, heterogeneous landscapes support greater species and habitat diversity (e.g., Kreft and Jetz 2007 at a global scale; local Bay Area studies are under way). This diversity means that source populations of native plants and animals that may be favored under future climates often occur in close proximity to sites they may be able to colonize in the future.

Conserving high levels of climatic heterogeneity may be accomplished by priority acquisition of large areas, heterogeneous sites (e.g., rugged topography), and improved connectivity among existing reserves, especially along steep climate gradients. Connectivity may be accomplished by acquisition or other legal protections for essential corridors, or through restoration efforts, invasive control, and changes in management of working landscapes that enhance permeability for wildlife and support greater native biodiversity (Heller and Zavaleta 2009). All of these approaches are the subject of ongoing research, and the SFBA is positioned to be a key testing ground for the integration of research and management in relation to connectivity planning and climate change (see Section 2.5 above). Various online tools are now available to query and integrate spatial data regarding biodiversity, habitat heterogeneity, and related information to inform conservation decision-making (e.g., Department of Fish and Game ACE-II project and the Bay Area Open Space Council's Conservation Lands Network Explorer tool).

4.2 Restoration Ecology and Ecosystem Management

The history or current status of restoration ecology in the SFBA is beyond the scope of this review (see Williams and Faber [2001] for a discussion of restoration in the San Francisco Bay estuary). Active management, including restoration, of natural and semi-natural ecosystems will continue to be of great importance in this century, particularly in the highly fragmented landscape of a major urban area like the SFBA. Restoration of riparian corridors is a high priority, as it serves simultaneous objectives of enhancing water quality, restoring critical habitat, and providing corridors for wildlife movement through suburban areas, agricultural lands, and open space. Seavy et al. (2009) argue that riparian conservation takes on increasing importance in the face of climate change, to minimize negative impacts on wildlife and enhance habitat heterogeneity and landscape resilience.

One subject that merits greater attention is the criteria used for selection of source material in restoration (see Rice and Emery 2003; Suding 2011). There is a strong tradition in conservation and restoration of focusing on local genotypes, both to maintain genetic diversity at a landscape scale and to benefit from any local adaptation of populations that have historically occupied a site or environmentally similar sites. In the face of rapidly changing conditions, the rationale for selecting local genotypes may, in part, be lost. The maintenance of genetic diversity is a priority target of conservation efforts, but the presumed greater success of locally adapted genotypes may no longer apply and may even reduce the chances of successful establishment of new populations. Two alternative strategies present themselves. One is a research intensive approach to model future climates and study patterns of adaptive variation across the range of a species. This would then allow the selection of optimal genotypes for future conditions, and this approach is being actively pursued in agriculture and forestry. In natural ecosystems, an alternative strategy is to intentionally plant a high diversity of genotypes collected from diverse environments across the range of a species, and allow the most successful genotypes to establish through the process of natural selection. This approach may lead to a loss of genetic diversity across populations at a landscape scale, but could be highly cost-effective to enhance success of restoration projects in the face of uncertain projections of future climate and imperfect knowledge of current adaptive variation within species. As species move into new communities and regions, either with or without human intervention, the concepts of “local source populations” and “native” versus “non-native” species will become increasingly ambiguous and will require re-evaluation.

As a general principle, adaptive management strategies that incorporate new information and changing conditions will be critical to ecosystem management. Management actions may be intended to: resist climate change, delaying undesired effects; enhance resilience of natural systems, such that they can accommodate change and disturbance while maintaining essential ecosystems functions; or respond actively to accommodate change by facilitating ecosystem responses to changing conditions (CA DFG 2011). In many cases, these actions will require realignment of management goals, as it will not be possible to restore systems to historical conditions or to manage for the historical range of variability. Management targets in many cases will have to be based on the rapidly changing and anticipated future conditions.

For example, major disturbances, such as fire, disease, or strong drought, combined with changing climate (particularly if a series of hot or dry years follows a disturbance event), could trigger critical transitions in which succession follows an alternative trajectory leading to establishment of new vegetation types. Restoration of the previously established vegetation may be difficult under new climate conditions, or may not succeed in the long run as climate changes become progressively more extreme (see Suding 2011). In these circumstances, management actions that enhance establishment of new species and vegetation types not previously native to a site may be the best choice. Disturbances create opportunities for rapid spread and establishment of invasive species, and intensive management may be necessary to promote establishment of native plants, whether they are species that previously occupied the site or newly establishing populations.

As discussed above, geographic range shifts are one of the primary responses of plants and animals during episodes of climate change. For some species, managed relocation (or assisted migration), in which new populations of species are intentionally established beyond the edge of the current range, may represent the only viable alternative to conserve wild populations in the face of climate change. A vigorous debate is under way among ecologists and conservation biologists regarding the necessity and wisdom of managed relocation (Richardson et al. 2009), as the track record of ecological surprises following accidental and intentional introduction of species outside their native range is cause for considerable concern. Reintroductions of endangered butterfly species are under way at several Bay Area sites, but we are not aware at this time of any proposals to translocate species from or to the Bay Area in relation to concerns over climate change impacts. This subject will require further discussion and analysis in the context of the Bay Area and California as a whole.

Section 5: Conclusions

The San Francisco Bay Area is a region of high priority for ongoing efforts to conserve native biodiversity and maintain high levels of ecosystems services in the face of twenty-first century climate change. The challenge in the Bay Area, as elsewhere, will be to manage for continued ecological change that fosters biodiversity conservation and ecosystem services. An integrated approach that incorporates terrestrial and freshwater ecosystems, the Bay itself, and the adjacent coastal and marine environments will be critical. Actions to expand the network of protected open space and enhance the biodiversity value of the working landscapes will contribute both to biodiversity preservation and the maintenance of ecosystem services in the twenty-first century. Conservation of heterogeneous landscapes, and improved connectivity among open space areas, is expected to enhance ecological resilience in the face of climate change. The array of academic, governmental and non-governmental organizations, combined with public support for environmental protection and conservation, make the Bay Area ideally suited to pursue innovative climate adaptation strategies, as well as research and monitoring efforts, that could set strong precedents in California and beyond.

References

Ackerly, D. D., Loarie, S. R., Cornwell, W. K., Weiss, S. B., Hamilton, H., Branciforte, R., and Kraft, N. J. B. (2010) "The geography of climate change: implications for conservation biogeography." *Diversity and Distributions* 16, 476–487.

Ackerly, David D. (2012) Future Climate Scenarios for California: Freezing Isoclines, Novel Climates, and Climatic Resilience of California's Protected Areas. California Energy Commission. Publication number: CEC-500-2012-022.

Adam, D. P. (1988) Palynology of two upper Quaternary cores from Clear Lake, Lake County, California. U.S. Geological Survey Professional Paper 1363, 86pp.

Allan, J. D. (2004) "Landscapes and riverscapes: The influence of land use on stream ecosystems." *Annual Review of Ecology, Evolution, and Systematics* 35, 257–284.

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., Hogg, E. H., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S. W., Semerci, A., and Cobb, N. (2010) "A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests." *Forest Ecology and Management* 259, 660–684.

Anderson, K. (2006). *Tending the Wild: Native American Knowledge and the Management of California's Natural Resources.* University of California Press, Berkeley, California.

Atwater, B. F., and Hedel, C. W. (1976) *Distribution of tidal-marsh plants with respect to elevation and water salinity in the natural tidal marshes of the Northern San Francisco Bay Estuary, California.* U.S. Geological Survey Open-File Report 76-389.

Balmford, A., and Bond, W. (2005) "Trends in the state of nature and their implications for human well-being." *Ecology Letters* 8, 1218–1234.

Bartolome, J. W., Stroud, M. C., and Heady, H. F. (1980) "Influence of natural mulch on forage production on differing California annual range sites." *Journal of Rangeland Management* 33, 4–8.

Battelle Memorial Institute (2008) *Economic Valuation of San Francisco Bay Natural Resource Services. San Francisco Bay Subtidal Habitat Goals Project, Appendix 1-2*. State Coastal Conservancy, Oakland, California.

Bay Area Early Detection Network (2011) BAEDN report. Audubon Canyon Ranch, Stinson Beach California.

Bay Area Open Space Council (2011) *The Conservation Lands Network: San Francisco Bay Area Upland Habitat Goals Project Report*. Berkeley, California.

Bay Area Open Space Council. (2012) The Conservation Lands Network. http://www.bayarealands.org/.

Biondi, F., Cayan, D. R., and Berger, W. H. (1997) "Dendroclimatology of Torrey pine (Pinus torreyana Parry ex Carr.)." *The American Midland Naturalist Journal* 138, 237–251.

Broughton, J. M. (2004) "Prehistoric human impacts on California birds: Evidence from the Emeryville Shellmound avifauna." *Ornithological Monographs* 56, 1–90.

Burgess, S. S., Pittermann, J., and Dawson, T. E. (2006) "Hydraulic efficiency and safety of branch xylem increases with height in Sequoia sempervirens (D. Don) crowns." *Plant Cell and Environment* 29, 229–239.

Burgess, S. S. O., and Dawson, T. E. (2004) "The contribution of fog to the water relations of Sequoia sempervirens (D. Don): Foliar uptake and prevention of dehydration." *Plant Cell and Environment* 27, 1023–1034.

CADFG (California Department of Fish and Game) (2011) Unity, Integration and Action: DFG's Vision for Confronting Climate Change in California. http://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=37647.

Cai, L., and Ismail, J. (2006) Napa County visitor profile study and Napa County economic impact study. Napa County.

California Department of Water Resources (2009) California Water Plan 2009. California Department of Water Resources, Sacramento, California.

California Department of Conservation (2009) Farmland Mapping and Monitoring Program. Retrieved from CA DOC main page via Land Resource Protection, Farmland Mapping & Monitoring Program: http://www.conservation.ca.gov/dlrp/fmmp/Pages/index.aspx. State of California, Sacramento.

California Natural Resources Agency (2009) *2009 California Climate Adaptation Strategy*. Sacramento, California.

Caluza, R., Cox, P., Cromwell, D., Ferkovich, R. I., Gentry, G., Hartman, L. F., Henly, R., Keithley, C., Schultz, M. K., Lang, S., Larvie, K., Marose, R., Melvin, J., Meyer, T., McNees, L., Passovoy, D., Peasley, B., Robards, T. A., Rosenberg, M., Sapsis, D., Smith, T., Snyder, B., Spero, J. G., Thompson, J., Tuttle, C., and Walker, R. (2010) California's Forests and Rangelands: 2010 Assessment. California Department of Forestry and Fire Protection, Sacramento, California.

Cayan, D. R., Bromirski, P. D., Hayhoe, K., Tyree, M., Dettinger, M. D., and Flick, R. E. (2008) "Climate change projections of sea level extremes along the California coast." *Climatic Change* 87 (Suppl 1): S57–S73.

Cayan, D., Tyree, M., and Iacobellis, S. (2012) Climate Change Scenarios for the San Francisco Bay Region. California Energy Commission, Public Interest Energy Research Program. CEC-500-2012-042.

Cayan, D., Tyree, M., Dettinger, M., Hidalgo, H., Das, T., Maurer, E., Bromirski, P., Graham, N., and Flick, R. (2009) Climate Change Scenarios and Sea Level Rise Estimates for California 2008 Climate Change Scenarios Assessment., California Energy Commission, Public Interest Energy Research Program.

Cayan, D. R., Maurer, E., Dettinger, M. D., Tyree, M., Hayhoe, K., Bonfils, C., Duffy, P., and Santer, B. (2006) Climate change scenarios for California. FINAL white paper from California Climate Change Center. California Energy Commission CEC-500-2005-203-SF, Sacramento, California.

Chan, K. M. A., Shaw, M. R., Cameron, D. R., Underwood, E. C., and Daily, G. C. (2006) "Conservation Planning for Ecosystem Services." *Plos Biol* 4, e379–e379.

Chan, Y., and Spautz, H. (2008) Alameda Song Sparrow, Melospiza melodia pusillula. In California Bird Species of Special Concern: A ranked assessment of species, subspecies, and distinct populations of immediate conservation concern in California (D. W. Shuford and T. Gardall, eds.) pp. 419–424, California Department of Fish and Game, Sacramento, California.

Chaplin-Kramer, R. (2012) Climate Change and the Agricultural Sector in the San Francisco Bay Area: Changes in Viticulture and Rangeland Forage Production Due to Altered Temperature and Precipitation Patterns. California Energy Commission, Sacramento, California. CEC-500-2012-033.

Chiariello, N. R., and Field, C. B. (1996) Annual grassland responses to elevated CO_2 in long-term community microcosms. In *Carbon Dioxide, Populations, and Communities* pp. 139–157, Academic Press, San Diego.

Chiariello, N. R. (1989) Phenology of California grasslands. In *Grassland structure and function: California annual grasslands* (L. F. Huenneke and H. A. Mooney, eds.) pp. 47–58, Kluwer Acad. Publ, Dordrecht.

Chou, W. W., Silver, W. L., Jackson, R. D., Thompson, A. W., and Allen-Diaz, B. (2008) "The sensitivity of annual grassland carbon cycling to the quantity and timing of rainfall." *Global Change Biology* 14, 1382–1394.

Chuine, I., Yiou, P., Viovy, N., Seguin, B., Daux, V., and Ladurie, E. L. R. (2004) “Grape ripening as a past climate indicator.” *Nature* 432, 289–290.

Cloern, J. E., Knowles, N., Brown, L. R., Cayan, D., Dettinger, M. D., Morgan, T. L., Schoellhamer, D. H., Stacey, M. T., van der Wegen, M., Wagner, R. W., and Jassby, A. D. (2011) “Projected Evolution of California's San Francisco Bay-Delta-River System in a Century of Climate Change.” *Plos One*, **6,** e24465–e24465.

Collins, S. L., Knapp, A. K., Briggs, J. M., Blair, J. M., and Steinauer, E. M. (1998) “Modulation of diversity by grazing and mowing in native tallgrass prairie.” *Science* 280, 745–747.

Conant, R. T., Paustian, K., and Elliott, E. T. (2001) “Grassland management and conversion into grassland: Effects on soil carbon.” *Ecological Applications* 11, 343–355.

Connor, E. F., Hefernik, J., Levy, J., Moore, V. L., and Rickman, J. K. (2002) “Insect conservation in an urban biodiversity hotspot: The San Francisco Bay Area.” *Journal of Insect Conservation* 6, 247–259.

Conway, C. J., and Sulzman, C. (2007) “Status and habitat use of the California Black Rail in the Southwestern USA.” *Wetlands* 27, 987–998.

Corbin, J. D., Thomsen, M. A., Dawson, T. E., and D’Antonio, C. M. (2005) “Summer water use by California coastal prairie grasses: Fog, drought, and community composition.” *Oecologia* 145, 511–521.

Cornwell, William K., Stephanie Stuart, Aaron Ramirez, and David D. Ackerly (University of California, Berkeley). 2012. Climate Change Impacts on California Vegetation: Physiology, Life History, and Ecosystem Change. California Energy Commission. Publication number: CEC-500-2012-023.

Davis, S. D., and Mooney, H. A. (1985) “Comparative water relations of adjacent California shrub and grassland communities.” *Oecologia* 66, 522–529.

Dawson, T. E. (1998) “Fog in the California redwood forest: Ecosystem inputs and use by plants.” *Oecologia* 117, 476–485.

de Orduña, R. M. (2010) “Climate change associated effects on grape and wine quality and production.” *Food Research International* 43, 1844–1855.

Dole, K. P., Loik, M. E., and Sloan, L. C. (2003) “The relative importance of climate change and the physiological effects of CO_2 on freezing tolerance for the future distribution of Yucca brevifolia.” *Global Planet Change* 36, 137–146.

Dukes, J. S., Chiariello, N. R., Cleland, E. E., Moore, L. A., Shaw, M. R., Thayer, S., Tobeck, T., Mooney, H. A., and Field, C. B. (2005) “Responses of grassland production to single and multiple global environmental changes.” *Plos Biol* 3, 1829–1837.

Elith, J., and Leathwick, J. R. (2009) "Species distribution models: Ecological explanation and prediction across space and time." *Annual Review of Ecology Evolution and Systematics* 40, 677–697.

Elith, J., Graham, C. H., Anderson, R. P., Dudik, M., Ferrier, S., Guisan, A., Hijmans, R. J., Huettmann, F., Leathwick, J. R., Lehmann, A., Li, J., Lohmann, L. G., Loiselle, B. A., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., Overton, J. M., Peterson, A. T., Phillips, S. J., Richardson, K., Scachetti-Pereira, R., Schapire, R. E., Soberon, J., Williams, S., Wisz, M. S., and Zimmermann, N. E. (2006) "Novel methods improve prediction of species' distributions from occurrence data." *Ecography* 29, 129–151.

Ewing, H. A., Weathers, K. C., Templer, P. H., Dawson, T. E., Firestone, M. K., Elliott, A. M., and Boukili, V. K. S. (2009) "Fog water and ecosystem function: Heterogeneity in a California redwood forest." *Ecosystems* 12, 417–433.

Ferrier, S., and Guisan, A. (2006) "Spatial modelling of biodiversity at the community level." *Journal of Applied Ecology* 43, 393–404.

Fischer, D. T., Still, C. J., and Williams, A. P. (2008) "Significance of summer fog and overcast for drought stress and ecological functioning of coastal California endemic plant species." *Journal of Biogeography* 36, 783–799.

Fitter, A. H., and Fitter, R. S. R. (2002) "Rapid changes in flowering time in British plants." *Science* 296, 1689–1691.

Flint, A. L., and Flint, L. E. (2012) "Downscaling future climate scenarios to fine scales for hydrologic and ecologic modeling and analysis." *Ecological Processes* 1:2

Foin, T. C., Garcia, E. J., Gill, R. E., Culberson, S. D., and Collins, J. N. (1997) "Recovery strategies for the California clapper rail (Rallus longirostris obsoletus) in the heavily-urbanized San Francisco estuarine ecosystem." *Landscape and Urban Planning* 38, 229–243.

Gardali, T., and Evens, J. G. (2008) Salt Marsh Common Yellowthroat, Geothlypis trichas sinuosa. In *California Bird Species of Special Concern: A ranked assessment of species, subspecies, and distinct populations of immediate conservation concern in California* (D. W. Shuford and T. Gardall, eds.) 346–350, California Department of Fish and Game, Sacramento, California.

Gordo, O., and Sanz, J. J. (2006) "Temporal trends in phenology of the honey bee Apis mellifera (L.) and the small white Pieris rapae (L.) in the Iberian peninsula (1952–2004)." *Ecological Entomology* 31, 261–268.

Graham, A. (1999) *Late Cretaceous and Cenozoic history of North American vegetation.* Oxford University Press, New York.

Graves, W. R., and Schrader, J. A. (2008) "At the interface of phylogenetics and population genetics, the phylogeography of Dirca occidentalis (Thymelaeaceae)." *Am J Bot* 95, 1454–1465.

Greenleaf, S. S., and Kremen, C. (2006) "Wild bee species increase tomato production and respond differently to surrounding land use in Northern California." *Biological Conservation* 133, 81–87.

Griffin, L. M. (1998) *Saving the Marin-Sonoma coast.* Sweetwater Springs Press, Healdsburg, California.

Hart, J. F. (2003) "Specialty cropland in California." *Geographical Review* 93, 153–170.

Hayes, G. F., and Holl, K. D. (2003) "Cattle grazing impacts on annual forbs and vegetation composition of mesic grasslands in California." *Conservation Biology* 17, 1694–1702.

Hayhoe, K., Cayan, D., Field, C. B., Frumhoff, P. C., Maurer, E. P., Miller, N. L., Moser, S. C., Schneider, S. H., Cahill, K. N., Cleland, E. E., Dale, L., Drapek, R., Hanemann, R. M., Kalkstein, L. S., Lenihan, J., Lunch, C. K., Neilson, R. P., Sheridan, S. C., and Verville, J. H. (2004) "Emissions pathways, climate change, and impacts on California." *P Natl Acad Sci USA* 101, 12422–12427.

Heady, H. F. (1956) "Changes in a California annual plant community induced by manipulation of natural mulch." *Ecology* 37, 798–812.

Heady, H. F. (1965) The influence of mulch on herbage production in an annual grassland. Proceedings of the 9th International Grassland Congress, 1, 391–394.

Heberger, M., Cooley, H., Herrera, P., Gleick, P. H., and Moore, E. (2009) *The impacts of sea-level rise on the California coast.* Prepared by the Pacific Institute for the California Climate Change Center. California Energy Commission, Public Interest Energy Research Program.

Heberger, M., Cooley, H., Herrera, P., Gleick, P. H., and Moore, E. (2011) "Potential impacts of increased coastal flooding in California due to sea-level rise." *Climatic Change* 109(S1): S229–S249.

Heberger, M., H. Cooley, E. Moore, P. H. Gleick, and P. Herrera. (2012) *The impacts of sea-level rise on the San Francisco Bay.* California Energy Commission, Public Interest Energy Research Program. CEC-500-2012-014.

Hedrick, D. W. (1948) "The mulch layer of California annual ranges." *Journal of Rangeland Management* 1, 22–25.

Hegland, S. J., Nielsen, A., Lázaro, A., Bjerknes, A. L., and Totland (2009) "How does climate warming affect plant-pollinator interactions?" *Ecology Letters* 12, 184–195.

Heller, N. E., and Zavaleta, E. S. (2009) "Biodiversity management in the face of climate change: A review of 22 years of recommendations." *Biological Conservation* 142, 14–32.

Hickman, J. C. (1993) *The Jepson Manual: Higher plants of California.* University of California Press, Berkeley, California.

Hilty, J. A., Brooks, C., Heaton, E., and Merenlender, A. M. (2006) "Forecasting the effect of land-use change on native and non-native mammalian predator distributions." *Biodiversity and Conservation* 15, 2853–2871.

Huntsinger, L., Johnson, M., Stafford, M., and Fried, J. (2010) "Hardwood rangeland landowners in California from 1985 to 2004: Production, ecosystem services, and permanence." *Rangeland Ecology & Management* 63, 324–334.

Ingraham, N. L., and Matthews, R. A. (1995) "The Importance of Fog-Drip Water to Vegetation - Point-Reyes Peninsula, California." *Journal of Hydrology* 164, 269–285.

IPCC. (2007) *Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*

Isenberg, P., Florian, M., Frank, R. M., McKernan, T., McPeak, S. W., Reilly, W. M., and Seed, R. (2008) *Delta Vision Report: Our Vision for the California Delta.* State of California Resources Agency.

Janzen, H. H. (2004) "Carbon cycling in earth systems—a soil science perspective." *Agriculture Ecosystems & Environment* 104, 399–417.

Johnstone, J. A., and Dawson, T. E. (2010) "Climatic context and ecological implications of summer fog decline in the coast redwood region." *Proceedings of the National Academy of Sciences, USA* 107, 4533–4538.

Kohyani, P. T., Bossuyt, B., Bonte, D., and Hoffman, M. (2008) "Grazing as a management tool in dune grasslands: Evidence of soil and scale dependence of the effect of large herbivores on plant diversity." *Biological Conservation* 141, 1687–1694.

Krawchuk, M., and Moritz, M. (2012) Fire and climate change in California: Changes in the Distribution and Frequency of Fire in Climates of the Future and Recent Past (1911–2099). California Energy Commission, Public Interest Energy Research Program. CEC-500-2012-026.

Kreft, H., and Jetz, W. (2007) *Global patterns and determinants of vascular plant diversity.* Proceedings of the National Academy of Sciences, 104, 5925–5930.

Kremen, C., Williams, N. M., Aizen, M. A., Gemmill-Herren, B., LeBuhn, G., Minckley, R., Packer, L., Potts, S. G., Roulston, T. A., Steffen-Dewenter, I., Vazquez, D. P., Winfree, R., Adams, L., Crone, E. E., Greenleaf, S. S., Keitt, T. H., Regetz, J., and Ricketts, T. H. (2007) "Pollination and other ecosystem services produced by mobile organisms: A conceptual framework for the effects of land-use change." *Ecology Letters* 10, 299–314.

Kremen, C., Williams, N. M., Bugg, R. L., Fay, J. P., and Thorp, R. W. (2004) "The area requirements of an ecosystem service: Pollination by native bee communities in California." *Ecology Letters* 7, 1109–1119.

Kroodsma, D. A., and Field, C. B. (2006) "Carbon sequestration in California agriculture, 1980–2000." *Ecological Applications* 16, 1975–1985.

Kuchta, S. R., Parks, D. S., and Wake, D. B. (2009) "Pronounced phylogeographic structure on a small spatial scale: geomorphological evolution and lineage history in the salamander ring species Ensatina eschscholtzii in central coastal California." *Molecular Phylogenetics and Evolution* 50, 240–255.

Kueppers, L. M., Snyder, M. A., Sloan, L. C., Zavaleta, E. S., and Fulfrost, B. (2005) "Modeled regional climate change and California endemic oak ranges." *P Natl Acad Sci USA* 102, 16281–16286.

Largier, J. L., Cheng, B. S., and Higgason, K. D. (2010) *Climate Change Impacts: Gulf of the Farallones and Cordell Bank National Marine Sanctuaries.* Report of a Joint Working Group of the Gulf of the Farallones and Cordell Bank National Marine Sanctuaries Advisory Councils.

Lebassi, B., Gonzalez, J., Fabris, D., Maurer, E., Miller, N., Milesi, C., Switzer, P., and Bornstein, R. (2009) "Observed 1970–2005 cooling of summer daytime temperatures in coastal California." *Journal of Climate* 22, 3558–3573.

Lenihan, J. M., Bachelet, D., Neilson, R. P., and Drapek, R. (2008) "Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California." *Climatic Change* 87, S215–S230.

Lenihan, J. M., Drapek, R., Bachelet, D., and Neilson, R. P. (2003) "Climate change effects on vegetation distribution, carbon, and fire in California." *Ecological Applications* 13, 1667–1681.

Limm, E. B., Simonin, K. A., Bothman, A. G., and Dawson, T. E. (2009) "Foliar water uptake: A common water acquisition strategy for plants of the redwood forest." *Oecologia* 161, 449–459.

Loarie, S. R., Carter, B. E., Hayhoe, K., McMahon, S., Moe, R., Knight, C. A., and Ackerly, D. D. (2008) "Climate change and the future of California's endemic flora." *Plos One* 3, e2502.

Loarie, S. R., Duffy, P. B., Hamilton, H., Asner, G. P., Field, C. B., and Ackerly, D. D. (2009) “The velocity of climate change.” *Nature* 462, 1052–1055.

Lotze, H. K., Lenihan, H. S., Bourque, B. J., Bradbury, R. H., Cooke, R. G., Kay, M. C., Kidwell, S. M., Kirby, M. X., Peterson, C. H., and Jackson, J. B. C. (2006) “Depletion, degradation, and recovery potential of estuaries and coastal seas.” *Science* 213, 1806–1809.

Martínez-Solano, I., Jockusch, E. L., and Wake, D. B. (2007) “Extreme population subdivision throughout a continuous range: Phylogeography of Batrachoseps attenuatus (Caudata: Plethodontidae) in western North America.” *Molecular Ecology* 16, 4335–4355.

Marty, J. T. (2005) “Effects of cattle grazing on diversity in ephemeral wetlands.” *Conservation Biology* 19, 1626–1632.

Mayer, K. E., and W. F. Laudenslayer, eds. (1988) *A guide to wildlife habitats of California*. State of California, Department of Fish and Game. Sacramento, California.

Maurer, E. P., Brekke, L., Pruitt, T., and Duffy, P. B. (2007) “Fine-resolution climate projections enhance regional climate change impact studies.” *Eos Transactions Agu* 88, 504.

McCulley, R. L., Burke, I. C., Nelson, J. A., Lauenroth, W. K., Knapp, A. K., and Kelly, E. F. (2005) “Regional patterns in carbon cycling across the Great Plains of North America.” *Ecosystems* 8, 106–121.

McDowell, N., W. T. Pockman, C. D. Allen, D. D. Breshears, N. Cobb, T. Kolb, J. Plaut, J. Sperry, A. West, D. G. Williams, and E. A. Yepez. (2008) "Mechanisms of plant survival and mortality during drought: Why do some plants survive while others succumb to drought?" *The New Phytologist* 178, 719–739.

McFarlane, K. J., M. S. Torn, S. Mambelli, and T. E. Dawson. 2010. Soil carbon storage and turnover in an old-growth coastal redwood forest and adjacent prairie. American Geophysical Union Fall Meeting. San Francisco, California, USA.

McLaughlin, J. F., Hellmann, J. J., Boggs, C. L., and Ehrlich, P. R. (2002) “Climate change hastens population extinction.” *Proceedings of the National Academy of Sciences, USA* 99, 6070–6074.

Meentemeyer, R., Rizzo, D., Mark, W., and Lotz, E. (2004) “Mapping the risk of establishment and spread of sudden oak death in California.” *Forest Ecology and Management* 200, 195–214.

Memmott, J., Craze, P. G., Waser, N. M., and Price, M. V. (2007) “Global warming and the disruption of plant-pollinator interactions.” *Ecology Letters* 10, 710–717.

Merenlender, A. M., Huntsinger, L., Guthey, G., and Fairfax, S. K. (2004) “Land trusts and conservation easements: Who is conserving what for whom?” *Conservation Biology* 18, 65–75.

Merenlender, A. M., Reed, S., Kitzes, J., and Feirer, S. (2010) *Mayacamas Connectivity Report for the Sonoma County Agriculture and Open Space Preservation District.* 2010. Available at www.sonomaopenspace.org.

Merenlender, A. M., Reed, S. E., and Heise, K. L. (2009) "Exurban development influences woodland bird composition." *Landscape and Urban Planning* 92, 255–263.

Meyer, J. L., Sale, M. J., Milholland, P. J., and Poff, N. L. (1999) "Impacts of climate change on aquatic ecosystem functioning and health." *Journal of the American Water Resources Association* 35, 1373–1386.

Micheli, L., Flint, L., Flint, A., Kennedy, M., Weiss, S., and Branciforte, R. (2010) *Adapting to climate change: State of the Science for North Bay watersheds.* A report prepared for the North Bay Watershed Association by the Dwight Center for Conservation Science, Santa Rosa, California.

Miller-Rushing, A. J., Katsuki, T., Primack, R. B., Ishii, Y., Lee, S. D., and Higuchi, H. (2007) "Impact of global warming on a group of related species and their hybrids: Cherry tree (Rosaceae) flowering at Mt. Takao, Japan." *American Journal of Botany* 94, 1470–1478.

Minnich, R. A. (2008) *California's fading wildflowers: Lost legacy and biological invasions.* University of California Press, Berkeley, California.

Moore, A. A., and Palmer, M. A. (2005) "Invertebrate biodiversity in agricultural and urban headwater streams: Implications for conservation and management." *Ecol. Appl.* 15, 1169–1177.

Moyle, P. B., Quinones, R. B., and Kiernan, J. D. (2012) Effects of Climate Change on the Inland Fishes of California: With Emphasis on the San Francisco Estuary Region. California Energy Commission, Sacramento, California. CEC-500-2012-029.

Mullin, L. P., Sillett, S. C., Koch, G. W., Tu, K. P., and Antoine, M. E. (2009) "Physiological consequences of height-related morphological variation in Sequoia sempervirens foliage." *Tree Physiology* 29, 999–1010.

Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., and Kent, J. (2000) "Biodiversity hotspots for conservation priorities." *Nature* 403, 853–858.

Nelson, G. C. (2005) Drivers of change in ecosystem condition and services. In *Ecosystem and Human Well-Being: Scenarios* (A. Rola, O. Renn, and W. Weimer-Jehle, eds.) 173–222, Island Press, 1.

Nemani, R. R., White, M. A., Cayan, D. R., Jones, G. V., Running, S. W., Coughlan, J. C., and Peterson, D. L. (2001) "Asymmetric warming over coastal California and its impact on the premium wine industry." *Climate Research* 19, 25–34.

Oberlander, G. T. (1956) "Summer fog precipitation on the San Francisco peninsula." *Ecology* 37, 851–852.

Outdoor Industry Foundation (2006) The Active Outdoor Recreation Economy: California,

Parisien, M. A., and Moritz, M. A. (2009) "Environmental controls on the distribution of wildfire at multiple spatial scales." *Ecological Monographs* 79, 127–154.

Pfeffer, W. T., Harper, J. T., and O'Neel, S. (2008) "Kinematic constraints on glacier contributions to 21st century sea level rise." *Science* 321, 1340–1343.

Phillips, S. J., Anderson, R. P., and Schapire, R. E. (2006) "Maximum entropy modeling of species geographic distributions." *Ecological Modelling* 190, 231–259.

Ramage, B. S., and O'Hara, K. L. (2010) "Sudden Oak Death-Induced Tanoak Mortality in Coast Redwood Forests: Current and Predicted Impacts to Stand Structure." *Forests* 1, 114–130.

Raupach, M. R., G. Marland, P. Ciais, C. Le Quere, J. G. Canadell, G. Klepper, and C. B. Field. (2007) "Global and regional drivers of accelerating CO_2 emissions." *Proceedings of the National Academy of Sciences of the United States of America* 104**,** 10288–10293.

Rice, K. J., and Emery, N. C. (2003) "Managing microevolution: Restoration in the face of global change." *Frontiers in Ecology and the Environment* 1, 469–478.

Richards, C., Johnson, L. B., and Host, G. E. (1996) "Landscape-scale influences on stream habitats and biota." *Canadian Journal of Fisheries and Aquatic Sciences* 53, 295–311.

Richardson, D. M., Hellmann, J. J., McLachlan, J. S., Sax, D. F., Schwartz, M. W., Gonzalez, P., Brennan, E. J., Camacho, A., Root, T. L., Sala, O. E., Schneider, S. H., Ashe, D. M., Clark, J. R., Early, R., Etterson, J. R., Fielder, E. D., Gill, J. L., Minteer, B. A., Polasky, S., Safford, H. D., Thompson, A. R., and Vellend, M. (2009) "Multidimensional evaluation of managed relocation." *Proceedings of the National Academy of Sciences, USA* 106, 9721–9724.

Rosenzweig, C., Casassa, G., Karoly, D. J., Imeson, A., Liu, C., Menzel, A., Rawlins, S., Root, T. L., Seguin, B., and Tryjanowski, P. (2007) Assessment of observed changes and responses in natural and managed systems. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contributions of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, eds.) pp. 79–131. Cambridge University Press, Cambridge, UK.

Sala, O. E., Parton, W. J., Joyce, L. A., and Lauenroth, W. K. (1988) "Primary production of the central grassland region of the United States." *Ecology* 69, 40–45.

Salah-Mars, S., and McCann, M. W. (2008) Delta Risk Management Strategy. Phase 1. Technical Memorandum: Climate Change (U. S. A. C. O. Engineers and D. O. F. A. Game, eds.). California Department of Water Resources, Sacramento, California.

San Francisco Estuary Project (1991) San Francisco Estuary Project status and trends report on wetlands and related habitats in the San Francisco Estuary. ABAG Public report to US-EPA. San Francisco Estuary Project, Oakland, California.

Schoellhamer, D. H. (2011) "Sudden Clearing of Estuarine Waters upon Crossing the Threshold from Transport to Supply Regulation of Sediment Transport as an Erodible Sediment Pool is Depleted: San Francisco Bay, 1999." *Estuaries and Coasts* 34, 885–899.

Schroter, D., Cramer, W., Leemans, R., Prentice, I.C., Araujo, M. B., Arnell, N. W., Bondeau, A., Bugmann, H., Carter, T. R., Gracia, C. A., de la Vega-Leinert, A. C., Erhard, M., Ewert, F., Glendining, M., House, J. I., Kankaanpaa, S., Klein, R. J. T., Lavorel, S., Lindner, M., Metzger, M. J., Meyer, J., Mitchell, T. D., Reginster, I., Rounsevell, M., Sabate, S., Sitch, S., Smith, B., Smith, J., Smith, P., Sykes, M. T., Thonicke, K., Thuiller, W., Tuck, G., Zaehle, S., and Zierl, B. (2005) "Ecosystem service supply and vulnerability to global change in Europe." *Science* 310, 1333–1337.

Seavy, N. E., Gardali, T., Golet, G. H., Griggs, F. T., Howell, C. A., Kelsey, T. R., Small, S., Viers, J. H., and Weigand, J. F. (2009) "Why climate change makes riparian restoration more important than ever." *Ecological Restoration* 27, 330–338.

Shaw, M. R., Pendleton, L., Cameron, D., Morris, B., Bratman, G., Bachelet, D., Klausmeyer, K., MacKenzie, J., Conklin, D., Lenihan, J., Haunreiter, E., and Daly, C. (2009) *The impact of climate change on California's ecosystem services.* California Energy Commission, CEC-500-2009-025-D, Sacramento, California.

Shaw, M. R., Zavaleta, E. S., Chiariello, N. R., Cleland, E. E., Mooney, H. A., and Field, C. B. (2002) "Grassland responses to global environmental changes suppressed by elevated CO_2." *Science* 298, 1987–1990.

Shellhammer, H. S. (1989) "Salt marsh harvest mice, urban development, and rising sea levels." *Conservation Biology* 3, 59–65.

Sicke, W. S., Lund, J. R., and Medillín-Azuara, J. (2012) Climate Change Adaptations for Local Water Management in the San Francisco Bay Area. California Energy Commission, Public Interest Energy Research Program. CEC-500-2012-036.

Sillett, S. C., Van Pelt, R., Koch, G. W., Ambrose, A. R., Carroll, A. L., Antoine, M. E., and Mifsud, B. M. (2010) "Increasing wood production through old age in tall trees." *Forest Ecology and Management* 259.

Simonin, K. A., Santiago, L. S., and Dawson, T. E. (2009) "Fog interception by Sequoia sempervirens (D. Don) crowns decouples physiology from soil water deficit." *Plant, Cell & Environment* 32, 882–892.

Sloan, D. (2006) *Geology of the San Francisco Bay Region.* University of California Press, Berkeley, California.

Snyder, M. A., Sloan, L. C., Diffenbaugh, N. S., and Bell, J. S. (2003) "Future climate change and upwelling in the California Current." *Geophysical Research Letters* 30, 1–4.

Snyder, M. A., and Sloan, L. C. (2005) "Transient future climate over the western United States using a regional climate model." *Earth Interactions* 9, 1–21.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Hiller, eds. (2007) *Climate Change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge Univ. Press: Cambridge, UK.

Spautz, H., and Nur, N. (2008a) Samuel's Song Sparrow, Melospiza melodia samuelis. In California Bird Species of Special Concern: A ranked assessment of species, subspecies, and distinct populations of immediate conservation concern in California (D. W. Shuford and T. Gardall, eds.) 412–418, California Department of Fish and Game, Sacramento, California.

Spautz, H., and Nur, N. (2008b) Suisun Song Sparrow, Melospiza melodia maxillaris. In *California Bird Species of Special Concern: A ranked assessment of species, subspecies, and distinct populations of immediate conservation concern in California* (D. W. Shuford and T. Gardall, eds.) 405–411, California Department of Fish and Game, Sacramento, California.

Spencer, W. D., Beier, P., Penrod, K., Winters, K., Paulman, C., Rustigian-Romsos, H., Strittholt, J., Parisi, M., and Pettler, A. (2010) California Essential Habitat Connectivity Project: A strategy for conserving a connected California. Prepared for California Department of Transportation, California Department of Fish and Game, and Federal Highways Administration. California Department of Transportation, Sacramento, California.

Stewart, W., Cromwell, D., Zimny, C., Marose, R., and Henly, R. (2003) *The Changing California: Forest and Range 2003 Assessment.* California Department of Forestry and Fire Protection.

Stohlgren, T. J., Schell, L. D., and Vanden Heuvel, B. (1999) "How grazing and soil quality affect native and exotic plant diversity in rocky mountain grasslands." *Ecological Applications* 9, 45–64.

Stralberg, D., M. Brennan, J. C. Callaway, J. K. Wood, L. M. Schile, et al. (2011) "Evaluating Tidal Marsh Sustainability in the Face of Sea-Level Rise: A Hybrid Modeling Approach Applied to San Francisco Bay." *PLoS ONE* 6(11): e27388.

Stralberg, D., Herzog, M., Nur, N., Tuxen, K., and Kelly, M. (2010) "Predicting avian abundance within and across tidal marshes using fine-scale vegetation and geomorphic metrics." *Wetlands* 30, 475–487.

Stralberg, D., Jongsomjit, D., Howell, C. A., Snyder, M. A., Alexander, J. D., Wiens, J. A., and Root, T. L. (2009) "Re-Shuffling of Species with Climate Disruption: A No-Analog Future for California Birds?" *Plos One* 4, e6825–e6825.

Suding, K. N. (2011) "Toward an Era of Restoration in Ecology: Successes, Failures, and Opportunities Ahead." *Annual Review of Ecology, Evolution, and Systematics* 42, 465–487.

Suttle, K. B., Thomsen, M. A., and Power, M. E. (2007) "Species interactions reverse grassland responses to changing climate." *Science* 315, 640–642.

Trulio, L., J. Callaway, and S. Crooks. (2007) A white paper on carbon sequestration and tidal salt marsh restoration. Viewed at: http://www.southbayrestoration.org/pdf_files/Carbon%20Sequestration%20Dec%2020%2007.pdf.

United Nations Environment Programme (2005) *The Millennium Ecosystem Assessment.* United Nations, New York, NY.

Veloz, S., N. Nur, L. Salas, D. Stralberg, D. Jongsomjit, J. Wood, L. Liu, and G. Ballard. (2011) *Tidal marsh bird population and habitat assessment for the San Francisco Estuary under future climate change conditions.* Version 1.0. Report to the California Landscape Conservation Cooperative.

Vihervaara, P., Ronka, M., and Walls, M. (2010) "Trends in ecosystem service research: Early steps and current drivers." *Ambio* 39, 314–324.

Visser, M. F., and Both, C. (2005) "Shifts in phenology due to global climate change: The need for a yardstick." *Proceedings of the Royal Society of London* 272, 2561–2569.

Vorosmarty, C. J., Leveque, C., and Revenga, C. (2005) Fresh Water. In Ecosystems and Human Well-Being: Current State and Trends (F. Rijsberman, R. Costanza and P. Jacobi, eds.) 165–207, Island Press, 1.

Wallis, M. J., Ambrose, M. R., and Chan, C. C. (2008) "Climate change: Charting a water course in an uncertain future." *Journal of American Water Works Association* 100, 70–79.

Weathers, K. C. (1995) "Cloud deposition to a spruce forest edge." *Atmospheric Environment* 29, 665–672.

Weiss, S. B., and Weiss, A. D. (1998) "Landscape-level phenology of a threatened butterfly: A GIS-Based modeling approach." *Ecosystems* 1, 299–309.

Weiss, S. B., Murphy, D. D., and White, R. R. (1988) "Sun, slope, and butterflies—topographic determinants of habitat quality for Euphydryas editha. *Ecology* 69, 1486–1496.

Westerling, A. L., Bryant, B. P., Preisler, H. K., Holmes, T. P., Hidalgo, H. G., Das, T., and Shrestha, S. R. (2009) *Climate change, growth, and California wildfire.* California Energy Commission, CEC-500-2009-046-F, Sacramento, California.

Williams, A. P., Still, C. J., Fisher, D. T., and Leavitt, S.L. (2008) "The influence of summertime fog and overcast clouds on the growth of a coastal California pine: A tree ring study." *Oecologia* 156, 601–611.

Williams, C. D., Shuman, B. N., and Webb, T. I. (2001) "Dissimilarity analyses of Late-Quaternary vegetation and climate in eastern North America." *Ecology* 82, 3346–3362.

Williams, P. B., and Faber, P. M. (2001) "Salt marsh restoration experience in the San Francisco Bay Estuary." *J. Of Coastal Research* 27, 203–211.

Zavaleta, E. S., Shaw, M. R., Chiariello, N. R., Thomas, B. D., Cleland, E. E., Field, C. B., and Mooney, H. A. (2003) "Grassland responses to three years of elevated temperature, CO_2, precipitation and N deposition." *Ecol Monogr* 73, 585–604.

Glossary

C	carbon
CADFG	California Department of Fish and Game
CCD	Colony Collapse Disorder
CCSM	Community Climate System Model (NCAR)
CLN	Conservation Lands Network
cm	centimeters
CO_2	carbon dioxide
Delta	Sacramento-San Joaquin Bay Delta
GCM	General Circulation Models
GFDL	Geophysical Fluid Dynamics Laboratory
Gt	gigatons
ha	hectares
HadCM3	Hadley Centre Coupled Model version 3
IPCC	Intergovernmental Panel on Climate Change
km	kilometers
km yr^{-1}	kilometers per year
km^2	square kilometer
m	meters
NCAR	National Center for Atmospheric Research
PCM	Parallel Climate Model
PCM 1	warmer, wetter parallel climate model
RCM	Regional Climate Models
SFBA	San Francisco Bay Area
SOD	sudden oak death
SRES	Special Report on Emissions Scenarios
U.S. DOE	U.S. Department of Energy